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CONTRAST DEPENDENT INTERACTIONS IN THE DETECTION OF TWO-LINE STIMULI

by

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Abstract

This study investigates how well the detection of visual two-line stimuli as a function of contrast can be accounted for in terms of independent detection of their individual components. The expected detection probabilities of two-line stimuli under the assumption of independence were determined by way of a probability summation-based method developed by King-Smith and Kulikowski (1981).

Detection responses were obtained from two observers by means of a two-alternative forced choice method; five contrast levels were employed to obtain probability-of-seeing curves for all stimuli.

In the experiment to be reported, six two-line stimulus pairs were used. While line length (20 min),and interline distance (30 min) were the same for all two-line stimuli, the latter differed from one another in terms of position and/or orientation of one member of the pair. This arrangement allowed to test the hypothesis of independence over a domain of stimulus properties so far largely ignored in this context.

Averaging over contrast,a close agreement between expected and observed detection probabilities was found. Also,effects attributable to the orientational/positional characteristics of the stimuli did not reach significance. An analysis of the data as a function of contrast, however,revealed that about threshold the observed detection probabilities were significantly greater than expected from

independence, while the opposite occurred at the highest contrast levels.

These deviations from probability summation are shown to be accountable for in terms of lateral interactions among (psychophysically defined) "line detectors".The relevance of these findings is discussed in relation to the notions of receptive/perceptive fields and probability summation.

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I. INTRODUCTION

The experiment here presented was suggested by a series of studies by King-Smith and Kulikowski (1975,1981). These researchers endeavored to show that the detection of composite stimuli could be explained in terms of independent detection of their individual components.

In the opionion of the writer, this explanation of their results could not be considered to hold in general unless a wider array of stimulus parameters were brought to experimental investigation. King-Smith and Kulikowski's explanation, in fact,applies to that domain of spatial vision ,where interactive phenomena among visual detectors are expected to occur.

By testing King-Smith and kulikowski's hypothesis of independence over a larger set of stimuli, it was possible to pursue two closely related objectives.Firstly, a more critical test of their hypothesis was achieved. Secondly,some of the possible conditions of occurrence of spatial interactions among visual elements were investigated.

The determination of the nature of the relations among visual elements engaged in the analysis of spatial patterns is,it will be argued later,critical to the understanding of both perceptual coding and perceptual integration.

In the following section, the theoretical background that motivated King-Smith and Kulikowski's studies (1975,1981) is first discussed.Next,the literature about

lateral interactions in vision is reviewed.A detailed presentation of King-Smith and Kulikowski's paper (1981),together with a discussion of the significance of the notion of probability summation in the study of spatial vision will finally help to introduce the experiment.

A. Feature analyzers.

> "The ultimate task of spatial vision is the recognition of visual scenes. Most visual scientists operate on the assumption that this first requires the analysis of complex patterns into discrete subunits of some form or other, with each individual cell in the geniculostriate pathway responding only to certain attributes of the pattern which occur within a delimited area of the visual field.For those who hold this view, the first task in studying pattern vision is to identify the attributes or subunits into which a complex pattern is analyzed."
> De Valois and De Valois,1980,pp. 316-317).

This quotation reflects, and summarizes,an approach to "early" visual perception that has been pursued during the past twenty years, since "the dawn of the neurophysiological feature extraction era"(Juslez and Schumer,1981,p.575).
An era,as it is commonly acknowledged,pioneered by the now classical discoveries of Hubel and Wiesel (1962,1965,1968). on the receptive field organization of visual cortical cells.

These workers first reported the existence of "simple" cells in area 17 of the cat's visual brain responsive to quasinaturalistic features of visual stimuli such as bars or slits of specific widths and orientation or edges of particular direction. These cells were shown to feed "complex" cells responding to these same stimuli in any position and over a larger area.

Groups of complex cells,in their turn, were assumed to generate the receptive fields of even more complex cells responding to the proper stimulus configuration only if end-stopped (hypercomplex I), or to two bars combined to form specific angles (hypercomplex II).

These findings at first induced enthusiastic hopes that the basic elements of visual perception had been finally identified. Furthermore, it was assumed,although less explicitly, that a thorough knowledge of the receptive field organizations of the retinogeniculate cortical pathway would also lead to the solution of another major problem of pattern vision: that of perceptual integration.

The visual system ' ,it was conjectured,first breaks down a

'It is customary, in many areas of vision research,to refer to the phenomena under investigation as though they were the sole resultant of the functioning of the "visual system", rather than the product of the activity of an observer engaged in a visual task. This distinction,if thoroughly considered, may have far reaching consequences, which cannot be evaluated here. In this work,where much attention is paid to the neural bases of visual performance, the recourse to a physicalistic language was found to be convenient,if not entirely appropriate.This should not lead us to forget, however,that any psychophysical task is carried out by an observer in its entirety, rather than by a subsystem of his/her brain alone.

scene into its elementary features. The hierarchical organization of the cortical cells would then lead to the coding of progressively more complex patterns (see e.g. Konorsky,1967,and Barlow,1972).

With the progress of research,however,the appealing simplicity of this model came to be seriously questioned on several grounds.

The hope of solving the problem of perceptual organization receded following increased evidence that the hierarchical organization of area 17 is far less monolitical than originally assumed by Hubel and Wiesel (1962).

Sekuler(1974) and De Valois and De Valois (1980) review many physiological data in this regard. Among them,the discovery that simple and complex cells both receive monosynaptic input from the LGN;that complex cells have response properties unseen in simple cells;that the latter seem very similar to retinal and geniculate X cells,while complex cells resemble Y cells,thus suggesting the existence of parallel projections of two systems.

Zeiki (1978) summarizes many studies about the anatomical and physiological properties of cells in "later" visual areas (V2-V4 and the superior temporal sulcus) pointing to the existence of parallel processing of different dimensions of the visual stimuli in such regions,as opposed to the assumed serial ordering of neurons in terms of increasing complexity of response characteristics.

Hughes (1982) argues that the attempts to account for

pattern vision in terms of serial,hierarchical processing strategies beginning with feature analysis have been most directly threathened by behavioral evidence of substantial abilities for complex spatial vision in destriate animals sampled from several mammalian species (Spear and Braun,1969;Doty,1971; Killackey et al,1971;Pasik and Pasik,1971; Winans,1971;Humphrey,1974;Keating,1975; Hughes,1977;Sprague et al.,1977;Dineen, and Keating,1979).

While these studies, by disclosing the complexities of the neural organization of the visual cortex, have questioned the hope of achieving a straigthforward solution to the problem of perceptual integration by means of serial,hierarchical models of receptive fields organization, the feature detectors approach turned out to be problematical also with regard to delimiting detector properties in human psychophysics.

B. Spatial frequency filters

Some of the ideas underlying what has come to be known as the "spatial frequency filter model" are not recent (see Schade,1956).Truly influential in the promotion of this line of research,however, were the compelling arguments presented by Campbell and Robson (1968) about the existence,in the visual system, of multiple spatial frequency channels (physiologically interpretable as receptive fields of given sizes and types)tuned to narrow frequency ranges.
The fertile conjecture advanced by these workers is that the

visual system, rather than being tuned to Hubel and Wiesel's naturalistic features of visual scenes, can be better described as a kind of Fourier-like analyzing device,operating over complex stimuli by decomposing them in specific spatial frequency channels (spectral regions).

Sekuler (1974) reviewed many of the earlier psychophysical findings in support of this hypothesis. Several physiological studies (reviewed by De Valois and De Valois,I980),also point to the existence of cortical cells responsive to narrow spatial frequency ranges (Maffei and Fiorentini, 1973;Ikeda and Wright,1975;Schiller et al.,1976;Albrecht,1978; Movshon et al.,1978).

The interest raised by these findings induced several researchers to try and compare directly the feature detector model with the spatial filter model.Schiller et al.(1976),De Valois et al.(1978), Glezer and Cooperman (1977),were able to show that cells in area 17 of the striate cortex are more selectively tuned to spatial frequency than to bar width. Adaptation studies with one dimensional patterns revealed that the effects of adaptation to bars and sinusoidal gratings could be better predicted by an analysis of the Fourier components of the stimuli rather than by their widths or luminance profile per se (Blakemore and Campbell,1969,Sullivan et al.,1972,De Valois et al.,1978)

Several other experimental paradigms were utilized to compare the two models.Among them are the metacontrast studies of Weisstein's et al.(1972,1977),while May and

Mattheson(1976) and Green et al.(1976) employed color aftereffects.

Upon reviewing much of this literature, De Valois and De Valois concluded that

> "Both psychophysical and physiological evidence is converging on the position that the visual system (at least up to early cortical levels) is not analyzing patterns into bar and edges,but rather is passing the information in each spatial region through a set of two-dimensional frequency filters".(1980,p.327).

Sekuler (1974) and Julesz and Schumer (1981) seem less willing to adopt,on this same issue, such perentory a verdict.

The De Valois chose to characterize this problem in ontological terms.A different,perhaps more profitable alternative,lies in the reformulation of this same problem in (meta)linguistical terms. In this way,the conflict between the feature detectors and spatial frequency channels models might dissolve,or assume a different perspective.

Such an alternative has been pursued by King-Smith and Kulikowski:

> "For any visual element which perform a linear spatial integration of the intensity distribution of the object,a description of its spatial properties in terms of sensitivity (amplitude and phase) to different spatial frequencies is entirely equivalent

> to a description in direct spatial terms,i.e. spatial weighting functions.Thus,from this theoretical viewpoint,a description of the visual system in terms of Fourier analysis,may be neither more nor less 'valid' than a description in direct spatial terms".(1981,p.235)

The choice of one approach over the other,then, may be reduced to a question of linguistic convenience in the description of the response of visual elements to different stimuli:the direct spatial approach may be more adequate when dealing with spatially localized stimuli,while a Fourier-like analysis is more suitable for the characterization of responses to periodic stimuli.

Caelli (in press) also denies the existence of a necessary opposition between the trigger feature and the frequency analyzer views of spatial coding :

> "Narrow-band two-dimensional filter profiles do,by definition,detect spatially delimited orientation/size specific contrasts.They do correspond to specific spatial features of an image.For this reason the only possible distinction may be in terms of whether the filters are broad or narrow banded."

That the real issue at stake here concerns channels' bandwidth is evident in a recent series of papers (Shapley and Tolhurst,1973;King-Smith and Kulikowski,1975,1981;Glezer,1977;Graham,1977,1989).

Shapley and Tolhurst (1973),and Kulikowski and King-Smith (1973),in a series of treshold-summation experiments in which a combination of narrowband (sinusoidal) and broadband (aperiodic) stimili were used, argued for the existence of two major classes of channels,narrowband channels (or 'spatial frequency detectors') and broadband channels (or 'line-edge detectors',as one might still want to call them).

Graham (1977,1980),however,objected that these two major classes of detectors were inferred under the assumption of no variability in the responses of different channels to the stimuli. By postulating independent variability (or probability summation) among channels, these same data can be accounted for in terms of one class only of relatively narrow band channels.

Specifically,this result is obtained by by assuming a) that a stimulus is detected whenever at least one of the multiple channels detects it, and b) that the variability in different channels is uncorrelated.

Formally,if P(Stim) is the probability that the observer detects the stimulus, P_i(Stim) the probability that the ith channel detects the stimulus, and N the total number of channels, probability summation among multiple channels is defined as

$$P(Stim) = 1 - \prod_{i=1}^{N} \left[1 - P_i(Stim)\right]$$

In a successive paper, King-Smith and Kulikowski (1975)showed that the detection and recognition of multiple line stimuli (rectangular gratings) could be understood in terms of responses of independent localized detectors to individual lines. As Shown by Graham (1977,1980), to explain satisfactorily these findings,it is sufficient to postulate only one class of channels, together with the assumption of probability summation both among channels and within channels (i.e. over space).

Graham(1977,1980) interprets the channel structure of multiple-channels models as consisting of a set of two-dimensional arrays of receptive fields which, within a channel,are identical in all respects but for position in the visual field (obviously,the characteristics of receptive fields - size,orientation tuning etc. - vary from channel to channel).

In a model which includes probability summation across the spatial extent of a channel, the channel's response variability is assumed to come from the uncorrelated fluctuation of the response magnitudes at different points of the channel. In other words,a stimulus will be at threshold whenever a critical peak response is reached anywhere within the channel. Composite stimuli such as narrowly spaced lines will activate the channel at different locations, thus increasing the probability of a response. The characteristics of this response would depend upon the weighting functions of the the channel,or equivalently, upon

the channel's impulse response function.

King-Smith and Kulikowski claim that this bandwidth respone function is broader than previously assumed, and that the detection and recognition of a set of parallel lines could be understood in terms of independent detection of their individual components,when the spacing of these stimuli is 14 min. of arc or more.This distance suggests that the weighting functions of the detecting mechanisms cannot be broad,or multi-peaked.Since the width of the weighting function is inversely proportional to the width of the spatial frequency curve (modulating transfer function),this, in turn,suggests the existence of relatively broad frequency tuning curves,the ones to be expected from localized detectors.

The preceeding discussion will have achieved its purpose if it will have made clear the following points.
The dispute over two apparently conflicting views about the nature of the perceptual code can be largely reformulated,and thus partially dissolved,at a linguistic level.The language of Fourier analysis is a powerful and unifying tool which,however,by no means should be considered as antagonistic to, or preclude,the direct spatial approach. Within the Fourier-based paradigm,the above dispute reduces to the problem of channels bandwidth.

The idea of spatial frequency channels,from the first rudimentary single-channel model to the more sophisticated multiple-channels models has thus been expanded up to the

consideration of spatial arrangements within individual channels.King-Smith and Kulikowski have proposed that individual channels be regarded as consisting of spatial subunits.

The way in which these spatial subunits relate to each other, whether by probability summation alone, or by way of more complex interactive processes in the spatial domain, adds a further dimension to this development.

Whether one should regard the evolution of the idea of spatial frequency channels as a successful articulation of a simple psychophysical idea,or whether one should rather interpret this development as a threat to the explanatory validity of this construct,is an open question.

C. Visual spatial interactions

Lateral interactions in human vision have been psychophysically determined with the method of subtreshold summation (Fiorentini and Mazzantini,1966;Kulikowski and King-Smith, 1973;Rentschler and Fiorentini,1974;King-Smith and Kulikovski,1975;Hines,1976;Rentschler and Hilz,1976;Wilson,1978; Wilson et al.,1979).

This method consists of determining the increment threshold for a test-line displayed against a homogeneous background as a function of the distance of a subliminal,inducing line parallel to the first.Decrement in threshold for the test line are taken to reflect the effects of facilitatory interations between the two lines,while the

opposite holds true for threshold elevation.

The aforementioned studies consistently indicated that the threshold for the test line is lowest when the two lines are superimposed,and then decreases as the distance between the two stimuli increases up to a point where it becomes greater than it would be without the presence of the inducing line.

Under the (most problematical) assumption of a parallelism between electrophysiologically and psychophysically determined response profile characteristics of visual detectors,the well-known shape of these functions ('line-spread functions') is taken to reflect the internal properties of receptive/perceptive fields organization.
This organization is generally regarded as consisting of a central summative excitatory region flanked by two antagonistic inhibitory bands.
The extent of these bands seems to depend upon the orientation tuning of a detector:inhibitory interactions were found to be weaker for oblique lines than for horizontal and vertical ones (Rentschler and Fiorentini,1976).This organization resembles that of simple cortical cells as revealed by neurophysiological methods (see e.g.Bishop et al. 1971,1973).
Rentschler and Hilz (1976) also showed that,as the distance of the flanking line exceedes the extent of the inhibitory region, a facilitatory effect on the detection of the test line may occur.This effect is strongest at twice the

distance for maximum inhibition. Rentschler and Hilz argue that this facilitatory effect might be attributable to the inhibition of the inhibitory effect of background illumination in the vicinity of the test line,that is to disinhibition, in a way similar to that modeled by Hartline and Ratliff (1958) for the Limulus' eye.Evidence for disinhibition in the cat's LGN cells was found by Maffei and Fiorentini (1972) and Hammond (1973).It is to be noted,however, that in order for the facilitatory effect to occur,the contrast of the inducing line has to be at least 70% of that of the test line.In addition, the facilitatory effect becomes more substantial as the contrast of the flanking line is increased to a level equal to,or greater than,that of the test line.

Wilson et al (1979) noticed that the conditions for the appearance of this effect closely resemble those in which probability summation among independent detectors is likely to operate,and asked whether the latter could account for Rentschler and Hinz's findings.

To test this hypothesis, they arranged two different experimental conditions. In one of them, the subject was to detect three parallel lines of varying contrast superimposed over a background of uniform mean luminance.In the other, the subject's task was to respond only to a single central test line discarding possibly visible inducing lines. The data from the detection task were found to be well predictable in terms of a model in which independent simple

center-surround visual elements summate probabilistically over space. In the discrimination experiment,the spatial arrangement of test and flanking lines affected differentially the response.Discrimination was found to be significantly worse when the test line was flanked by the inducing lines on both sides of it than when the inducing lines were positioned on the same side of the test line. The latter configuration obviously satisfies the dishinibition model:if the test line is inhibited by the neighboring flanking lines,and the latter is inhibited by its twin line,then the first is freed from inhibition.These same two stimulus configurations,however,were found to be equally visible in the detection task,and well predicted in terms of probability summation.

While both Wilson and Rentschler agree that probability summation did likely occurr, the latter also reiterated that disinhibition was present,and becomes manifest in discrimination tasks.The experiment did not allow to distinguish among these hypotheses.

The kind of spatial interactions so far considered are supposedly taking place within the response area of individual visual detectors.What about spatial interactions between visual elements? To rephrase this question in terms more specifically related to the previously discussed literature: do line detectors (or line-spread functions, or subunits within spatial frequency channels) interact with each other,and if this is the case, under what conditions?

This question has been experimentally addressed in this work. A recent paper by King-Smith and Kulikowski (1981) is,in particular,at the origin of the research presented.

D. King-Smith and Kulikowski s experiments.

King-Smith and Kulikowski(1981) performed their study in order to establish how well the detection and the recognition of a two-line stimulus could be ascribed to independent detection of each line.

In their first experiment,two vertical bright lines of varying length (135 or 40 min of arc) were generated on the screen of an oscilloscope with mean luminance of 40 cd/m .

A two alternative forced choice method was used in which the stimuli were presented in one of two 40-msec intervals.On each trial,a single line was presented either to the right or to the left of the center of the display area,or both lines were simultaneously presented ,interline distance being varied between 3 and 30 min.

After each trial,the observer had to perform both a detection response,by indicating in which of the two intervals the stimulus was presented, and a"recognition" [2] response,by telling whether one or two lines had been displayed. All types of trials were presented at five different contrast levels,the four lower ones being

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[2] It is very dubious whether the term "recognition", as used by King-Smith and Kulikowski and other vision researchers,correctly applies to this and similar tasks:"identification" might be a better descriptor for this kind of responses.

0.1,0.2,0.3, and 0.5 log units below the highest contrast.

The authors analyzed their results first in terms of the following independent detection model.

Let $P(d/1)$ and $P(d/2)$ represent the probability of detecting,(that is of choosing the correct interval) one and two lines respectively. The model assumes that there is a probability p of an all-or-none response to a line by an appropriate detector,while there is no probability of response when no line is presented.

Accordingly,a single line will be detected if either

1) a visual response with probability p occurs in presence of the line,or

2) no response occurs (probability $1-p$),but the observer makes a correct guess (probability $1-p/2$).

Thus,the overall probability of detecting a single line is provided by the equation:

$$P(d/1)= p+(1-p)/2 = 1/2+p/2 \qquad (1)$$

The probability of a visual response,then,is:

$$p = 2P(d/1)-1 \qquad (2)$$

A two-line stimulus,assuming independent detection at each stimulus location, will be detected if either

1)a response to both lines occur(probability p^2),or

2)the left line,but not the right line is responded to,or viceversa (probability $2p\ (1-p)$),or

3) no visual response occurs (probability $(1-p)^2$, but the observer makes a correct guess (probability $1/2\ (1-p)^2$).

The overall probability of detection is thus:

$$P(d/2)=p^2+2p(1-p)+1/2(1-p)^2$$
$$=1/2+p-1/2\ p^2$$
$$=1-1/2\ q^2 \qquad (3)$$

where $q=1-p$

Thus, the model allows to predict P(d/2) from P(d/1) by using equations 2 and 3.

The results supported this basic independent detection formulation. In partial agreement with earlier findings, (King-Smith and Kulikowski, 1975), the independence-of-encoding hypothesis was found to hold for lines with spacing of 14 min or more. This distance is taken by the authors to represent the minimum spacing needed to ensure that each line is outside the receptive field of the other line detector, and thus represents a precondition for the applicability of the model.

The probability of detection and recognition of two lines, predicted by means of a quite straightforward extension of the basic independent detection model, was found to sligthly exceed the predictions. An overall fit to the data was obtained through a modification of the basic independent detection/recognition model in which variations of sensitivity, false positives, and responses from detectors responding to both lines ("bidetectors") were taken into account.

Substantially similar results were obtained from a related experiment in which the lines were presented in two orientations, vertical and oblique. The subject's task was to

indicate on each trial the orientation of the stimulus (a response shown to be equivalent to the detection response of the previous experiment),and to estabilish whether one or two lines had been presented.

This latter experiment is,and was meant to be, substantially similar to those carried out by Glezer et al.(1977). These workers found that the probability of correctly responding to two lines was significantly higher than the theoretical probabilities predicted by the assumption of independence.

This difference was greater when the distance between the lines was in the range 19-30 min,although it was noticeable also in the 4-12 min interval.When the spacing between the lines exceeded 30 min, expected and observed probabilities were found to coincide.Glezer et al. (1977) concluded that the recognition of two line stimuli must be attributed to the involvement of new functional mechanisms responding to composite stimuli.

These mechanisms were identified with 'grating detectors',since the critical spacing for the observed facilitations was found to be consistent with the estimated diameter of the receptive fields of units responsive to gratings of differing spatial frequencies (Glezer and Kostelyanets,1975).

It will be noted that in both interpretations no appeal is made to spatial interactions between visual detectors.The notion of probability summation,as said before,postulates independent,uncorrelated responses of visual elements to

composite stimuli. When,as in the case of recognition,the results appear to exceed the predictions, this discrepancy is explained away in terms of the independent activation of new units (Glezer et al),and/or in terms of the observer's fluctuations in sensitivity (King-Smith and Kulikowski).
While these assumptions may seem tenable,they might lead to the overlooking of important phenomena.In fact,an entirely reasonable alternative to these assumptions lies in the postulation of facilitatory spatial interactions between visual detectors.

This alternative is also theoretically far more appealing for the following reasons.
By virtue of their explanations, King-Smith and Kulikowski are bound to the assumption that the encoding of spatial stimuli is achieved,at least in its early phases,by independent mechanisms operating in parallel.If this is the case, It would be difficult to envisage how ,on this basis,a credible solution to the problem of perceptual integration,that must underlie the process of pattern recognition,could ever be achieved.

In fact,as Dodwell noted,

> "The major problem,if one agrees that feature detection is an important first step in visual processing, is how feature information is integrated into perceptual units - the old problem of perceptual Gestalt".(1982,p.801).

Many approaches to the problem of perceptual integration have been pursued throughout the years (see Dodwell,1970,1978,1982,and Zusne,1970,for reviews). Still,as noted by Caelli and Dodwell(in press), what has been so far conspicuously lacking is a concerted effort to relate the issue of pattern coding to that of perceptual integration.

By virtue of the above considerations,studies like those of King-Smith and Kulikowski (1975,1981) thus acquire a theoretical significance which goes beyond the spatial frequency filters vs. feature detectors dispute previously considered.

The search for the nature and conditions of occurrence of spatial interactions between visual detectors represents a preliminary step toward an integrated treatment of the problem of pattern perception.

According to Julesz and Schumer(1981,p.581), the heuristic value of the notion of probability summation lies in the possibility it offers of distinguishing purely statistical pooling effects from other,physiologically based pooling properties.

That this may not always (or even often)be the case is shown by Wilson's et al. study previously discussed (1979).The problem with probability summation lies in its non-linearity,which is also expected from physiological pooling effects, or neural connectivities (see e.g. Leake and Anninos,1976,Grossberg,1978).

The independence-of-encoding assumption,therefore,even when

it seems confirmed by data that fit a probability summation model,cannot be unambiguously demonstrated.In their two-interval experiment, which provided the best-fitting data,King-Smith and Kulikowski measured probability of detection for only one kind of stimuli in fixed configurations:straight lines of identical length,width and brightness, equidistant from the center of the display and presented together always parallel to each other in perfectly symmetrical positions.

The only spatial variable to be manipulated was distance,and a spacing of 14' or more was required to fit the basic independent detection behavior.While this model may seem appealing because of its simplicity,it is worth repeating that King-Smith and Kulikowski's data cannot distinguish between different kinds of non-linearities.To be persuasive,a probability summation model ought to be shown to be valid over a wider range of spatial variables. To wit,in order to be confident that the assumption of probability summation over space does not actually mask complex interactive phenomena in the spatial domain,it ought to be shown to be applicable irrespectively of different stimulus properties and configurations.

In the following chapter,an experiment is presented that is meant to bring to stricter experimental test the independence-of-encoding hypothesis. In order to make the results comparable to those of King-Smith and Kulikowski,the experimental paradigm was chosen so as to closely resemble

their two interval detection task.

As such, the following experiment can be seen as a replication and an extension of their study. The spacing between the stimuli has been kept fixed and at a value (d=30') that fully satisfies the conditions of applicability of King-Smith and Kulikowski's model, thus allowing a correct test of the latter.

In order to distinguish between probability summation over space and other kinds of spatial non-linearities, two important spatial properties of the stimuli to be detected are introduced: orientation and position.

Probability summation per se is not related to the various configurations that two stimuli varying in both orientation and position might generate. However, these configurations may well induce spatial interactions among visual detectors, thus giving rise to differences in sensitivity as indexed by detection measures.

It might be argued that, so far as Gestalt-like, "top-down" processes are allowed to play a significant role within the particular experimental conditions and parameter values of the following experiment, sensitivity ought to improve as a function of the structure of the stimuli (definable, e.g., in terms of orientation/position correlation, see Caelli and Dodwell, 1982, in press; Dodwell and Caelli, in press).

On the other hand, inhibitory interactions between detectors tuned to similar orientations, like those postulated by Carpenter and Blakemore (1973) could instead play a role, thus

originating results of opposite sign.A more detailed discussion of this issue will be attempted later.

II. THE EXPERIMENT.

A. Method.

Subjects

Two observers,the author and MMH, with corrected-to-normal vision, participated to all experimental sessions.

Apparatus and stimuli

The stimuli were presented on a Hewlett-Packard 1333a cathode-ray tube equipped with P15 phosphor.
A PDP11/34 computer executed all display, timing and scoring functions.

The observers sat in an acoustically controlled chamber,and faced the display surface at a distance of 40 cm., set by a headrest.
An overhead light illuminated the chamber,and generated a background luminance,as measured from the screen,at 10 cd/m^2.
The constancy, from day to day,of the luminous intensity of the cathode-ray tube, given a constant z-axis voltage, was insured by means of the following calibration procedure. A test patch consisting of a matrix of 81 evenly spaced dots, covering an area of 2.0 square mm. on the oscilloscope's screen, was plotted at a given z-value, and refreshed at a rate of 1 KHz. The luminance of the patch was measured with a Photo Research Spotmeter digital photometer (aperture=1

deg). The photometer was positioned at its minimal focal distance within a frame that hooked onto the face of the oscilloscope.The intensity gain of the point plotter was adjusted so as to give a constant reading of 18 cd/m^2.Daily calibration procedures were accomplished on the basis of readings from a digital voltmeter connected to the last stage of the oscilloscope's z-amplifier.

The display was initialized by pressing a hand-held button, two other buttons being used for responses.

The stimuli were assembled from 12 closely spaced dots, and plotted at the center of a square area outlined prior to the onset of a display by four dots and subtending 2.0 deg of visual angle.

The stimuli were lines of identical length (20' of arc) presented either individually or in pairs.In the latter condition,one of the two lines was always presented in the same orientation (vertical) and in the same position.Specifically,this line always appeared at a distance of 15' to the left of the center of the display area,with its middle point aligned along the horizontal axis with the geometrical centre of the display.
The middle point of all the lines presented to the right of the centre of the display area was always at a distance of 30' from the middle point of the left line.
These lines were displayed in one of three orientations: vertical,horizontal,and oblique (90,0,and -45 deg), and in two positions.In one of these,their middle point was aligned

along the horizontal axis with the centre of the display area, and thus with the middle point of the left line when both were presented.In the other,the middle point of these lines was displaced upwards in such a way that a diagonal line connecting this point with the centre of the left line was inclined at an angle of 30 deg (Fig.1;Fig.2 shows all the stimuli used and their grouping).

Experimental task

On all experimental trials the sequence of events was the following: upon pushing a button,the four dimly illuminated dots outlining a square appeared in the surround of the display area, to aid focussing and convergence.
By pressing the same button a second time,the four dots disappeared,to be immediately followed by a second 40msec display. The end of this interval was signaled by the reappearance of the four fixation dots. By pressing the same button another time,a second 40msec display ensued.
The observer had next to indicate in which of the two intervals a stimulus had been displayed by pressing one of two numbered buttons corresponding to each of the intervals.Following this response,the reappearance of the fixation dots signalled the start of another trial.

On each block of trials, the same three stimuli were each randomly presented ten times at each of five contrast levels,for a total of 150 trials. For all blocks,one of the

Figure 1. Representation of position and orientation of all the lines displayed at the right of the fixation point,and of the way they are related to the midpoint of the left vertical line.All two-line stimuli were composed of the left line together with one of the right lines.

A=B=30 min of arc.θ=30 deg.

Line length=20 min of arc.

Scale: 1 min=1 mm.

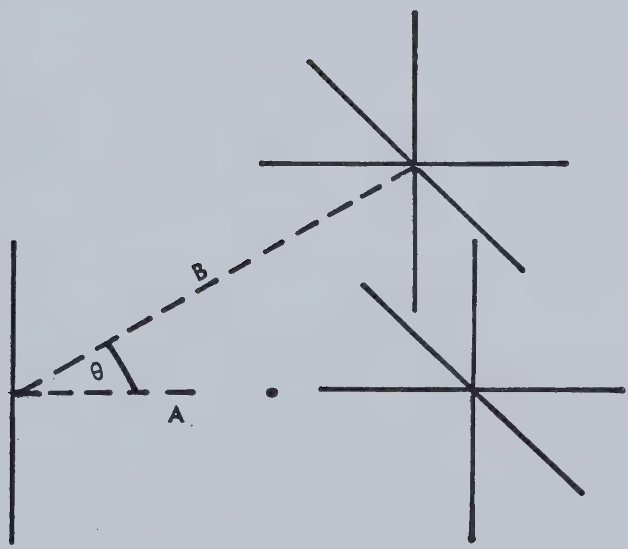
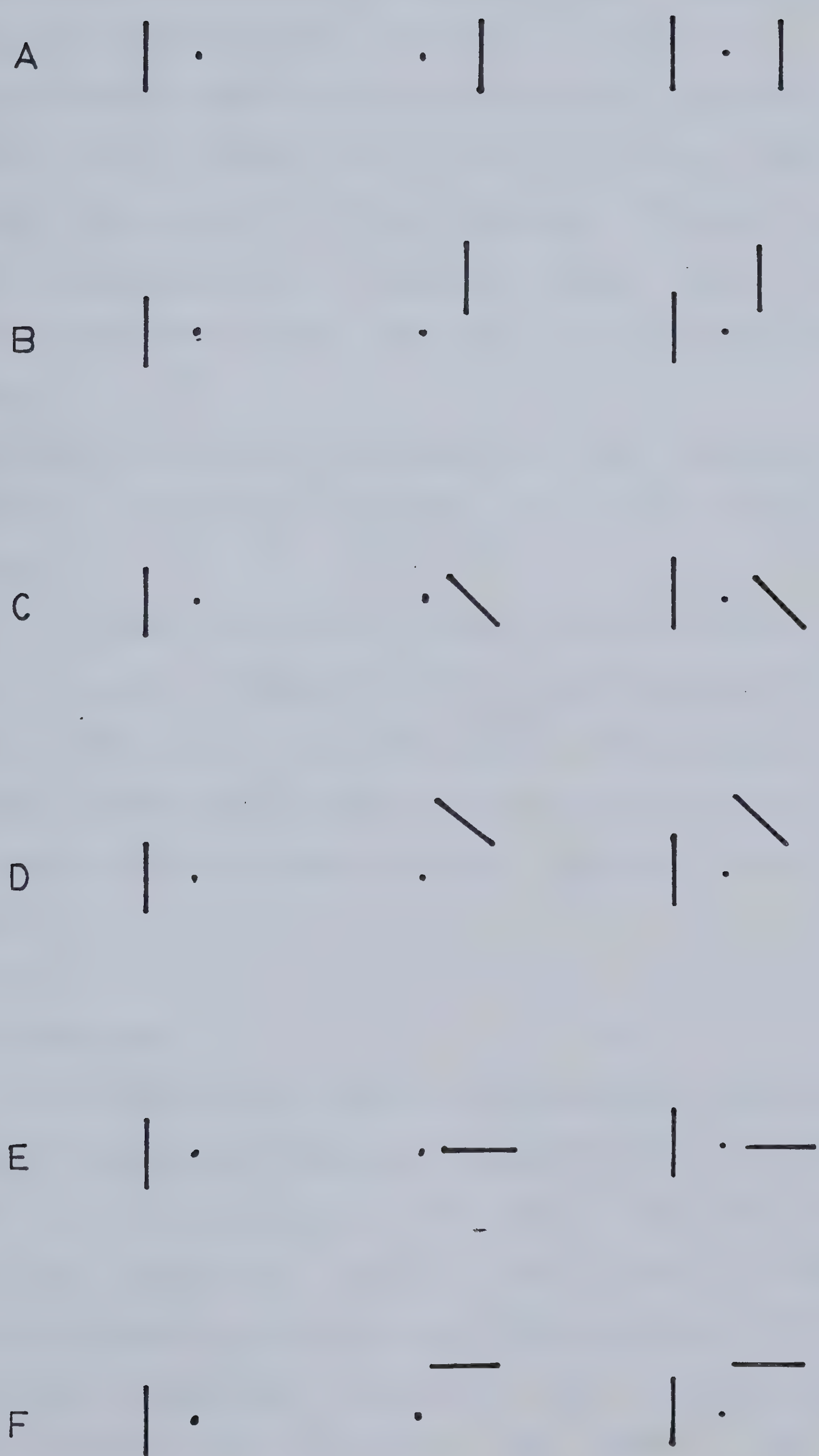

B
θ
A

Figure 2. Illustration of the six triads of stimuli used in the experiment.A block of trials consisted of the presentation of one of the triads of stimuli shown in the figure. Each member of the triad was randomly presented 10 times at each of the five contrast levels. This procedure was repeated ten times for each triad of stimuli.The 60 blocks of trials were delivered in random order.


A
B
C
D
E
F

stimuli was always the left vertical line presented alone. Within each block,a right line was also always presented: alone,and then together with the left line.
The factorial combination of orientation and position of the right lines yielded 3x2=6 triads of stimuli. Each block of trials was repeated 10 times,and order of block presentation was randomized.Each observer had thus to complete 3x5x10x10x6=9000 trials, and each stimulus was presented 500 times.
The number of correct responses to each stimulus at each contrast level was recorded at the end of each block of trials.

In order to select a set of contrast values that could yield a range of detection percentages spanning from near chance (50% in this two-alternative, forced choice paradigm) to near error free performance,the observers first undertook a series of pilot runs which are described in the following section.

B. Pilot runs

One observer,the author,was primarily involved in the task of selecting a suitable range of contrast values to be used in the experiment. To begin with,only individual vertical lines were used in the attempt of determining a contrast level which would yield approximately 50% correct detection responses. Relatively few trials were sufficient to identify this level,and to verify its relative

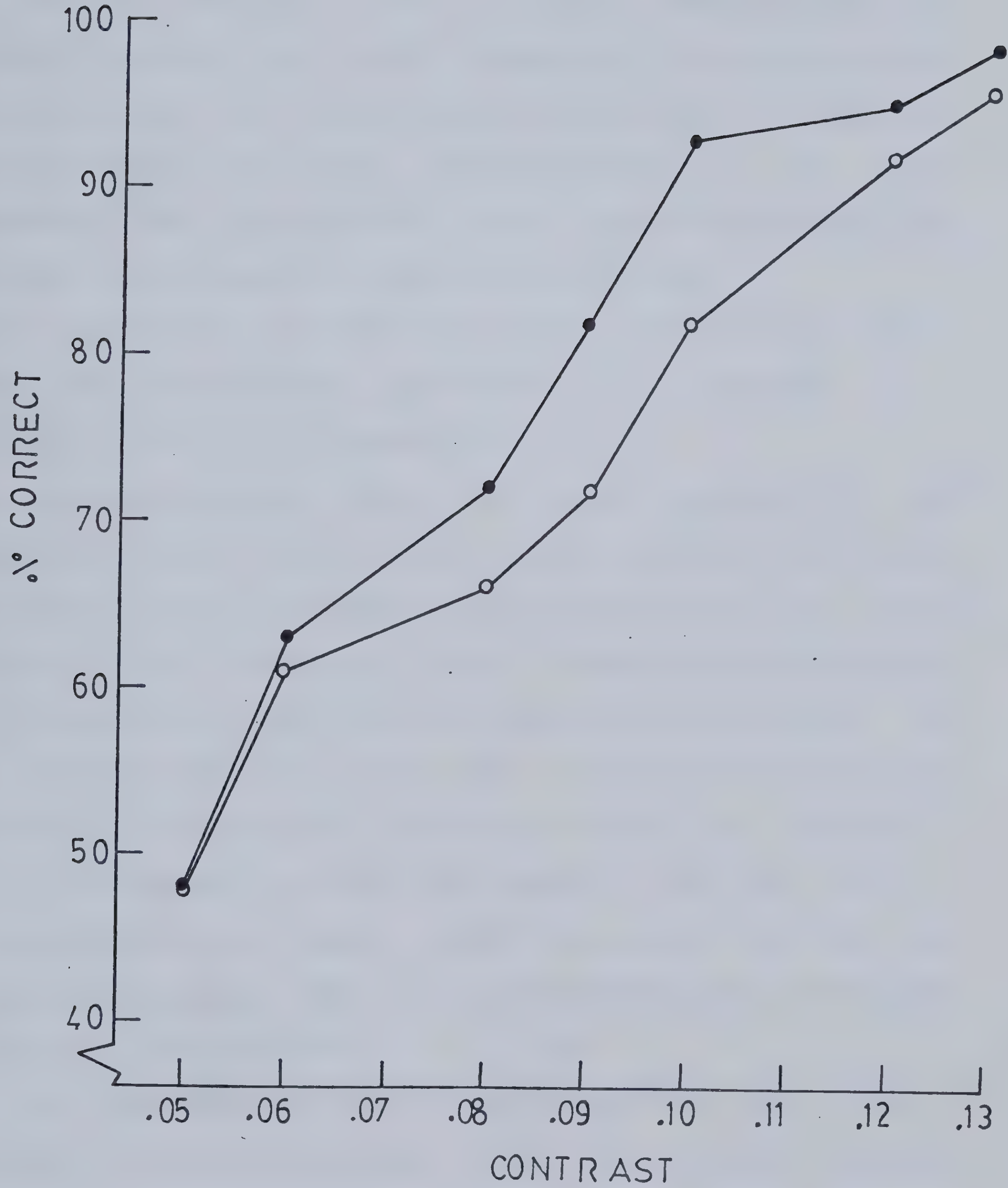
stability.This value (0.05) was taken as the one corresponding to the trheshold for detection.Next, six other values (0.06,0.08,0.09,0.1,0.12,0.13) were chosen to be used in further preliminary runs to determine whether satisfactory probability-of-seeing curves could thus be obtained. In these runs vertical one and two-line stimuli were used.

Given the requirements of the model that was to be tested, these values were to be chosen so that differences in detectability between individual and composite stimuli, if existing,could emerge.This requires that detection for single lines at each contrast level be made difficult enough so as to leave room for significant improvement in detection when two lines are presented, while at the same time allowing substantial and well-ordered detection values for individual stimuli.

The results of this part of the pilot study are presented in fig.3. As it can be seen,detection spans from a near-chance level to virtually perfect performance,and the visibility of two lines is, as expected, greater than the visibility of single stimuli at most contrast levels.

Further consideration of the data,however,revealed that in the last portion of these runs performance had noticeably improved.In order to avoid practice effect, it was decided to protract the preliminary runs until a stable level of performance was achieved.

Figure 3.Percentage of correct detection responses in preliminary runs plotted as a function of contrast. Open circles represent the data for a single vertical line displayed at the left of the fixation point. Solid circle are data for two vertical lines.


100
90
80
70
60
50
40
% CORRECT
.05
.06
.07
.08
.09
.10
.11
.12
.13
CONTRAST

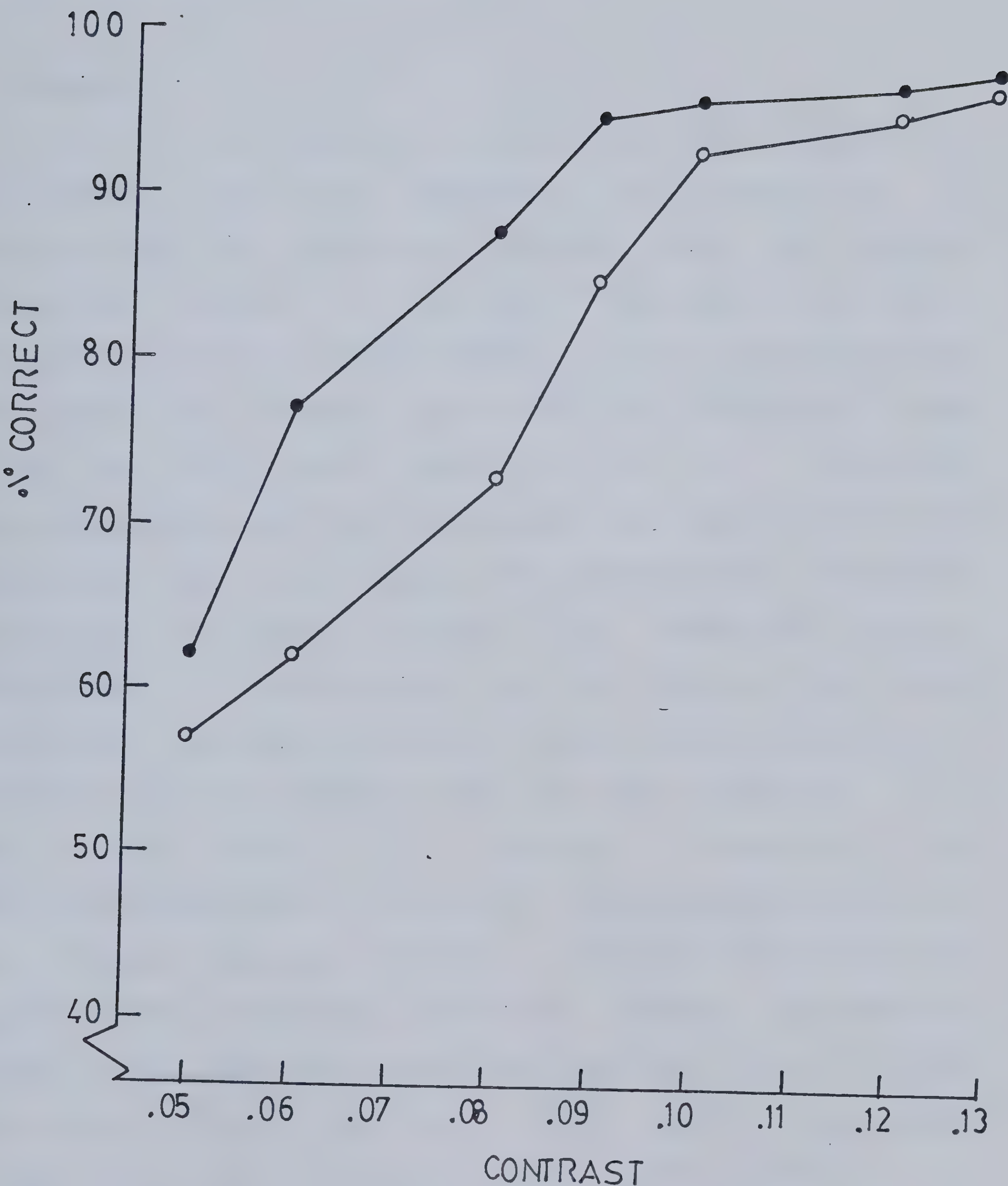
In this phase,all the stimuli to be used during the experiment were used. The results are presented in fig.4. As it can be noticed, a larger difference between single and composite stimuli was found in comparison with the data from the previous runs. Although detection improved remarkably for both single and double lines,detection of the latter improved more substantially than that of the former,thus accounting for the difference above mentioned.

More importantly,particularly in the case of double lines, near perfect,asymptotic performance was achieved at a contrast level of 0.09 (see fig.4).

As a consequence,this value was finally selected as the uppermost level to be used in the experiment. Although a noticeable overall increase in detectability at the lowest contrast level was also found, it was decided to maintain the latter as the one corresponding to threshold,since this was indeed the case for some of the stimuli. Given the substantial narrowing of the contrast range thus achieved,it was also decided to reduce the number of contrast levels to five,the previous number being too large for the new restricted range. The final selected contrast values were 0.05,0.06,0.07,0.08.0.09.

As mentioned before, one observer only was primarily involved in this preliminary phase. The second observer, MMH,was also successively exposed to a large number of preexperimental trials, during which the range of contrast values was progressively reduced until she provided evidence

Figure 4.Percentage of correct detection responses in the second half of the pilot runs.In this phase,all single and two-line stimuli to be used in the experiment proper were employed. Open circles are data for the set of single lines, solid circles are data for the set of two-line stimuli.


100
90
80
70
60
50
40
% CORRECT
.05
.06
.07
.08
.09
.10
.11
.12
.13
CONTRAST

of being able to perform satisfactorily at the contrast levels selected for the experiment.

C. Results

The F distribution is relatively not affected by deviations from the assumption of homogeneity of variance,and the resulting positive bias in testing treatment effects is of small magnitude (Kirk,1968). Nonetheless,since a slight tendency toward proportionality of means and standard deviations was suspected in some cases,the data were subjected to a logarithmic transformation,and the ANOVAs described below were carried out over both transformed and untransformed scores.The resulting F tests yielded fully compatible results. Detection of One-line and two-line stimuli was first separately analyzed by way of repeated measures ANOVAs (a Subjects (2) X Orientation (90,0,-45 deg) X Position (= 0 and 30 deg) X Contrast (5)design). For one-line,right-positioned stimuli (average detection= 64 %), the factor contrast yielded a strongly significant main effect ($F(4,4)=94.43, p < 0.01$);the overall psychometric function for individual lines relating detection to contrast is plotted in fig.5. The other factor closely approaching significance was orientation ($F(2,2)=16.79$, $p<0.06$).[3]

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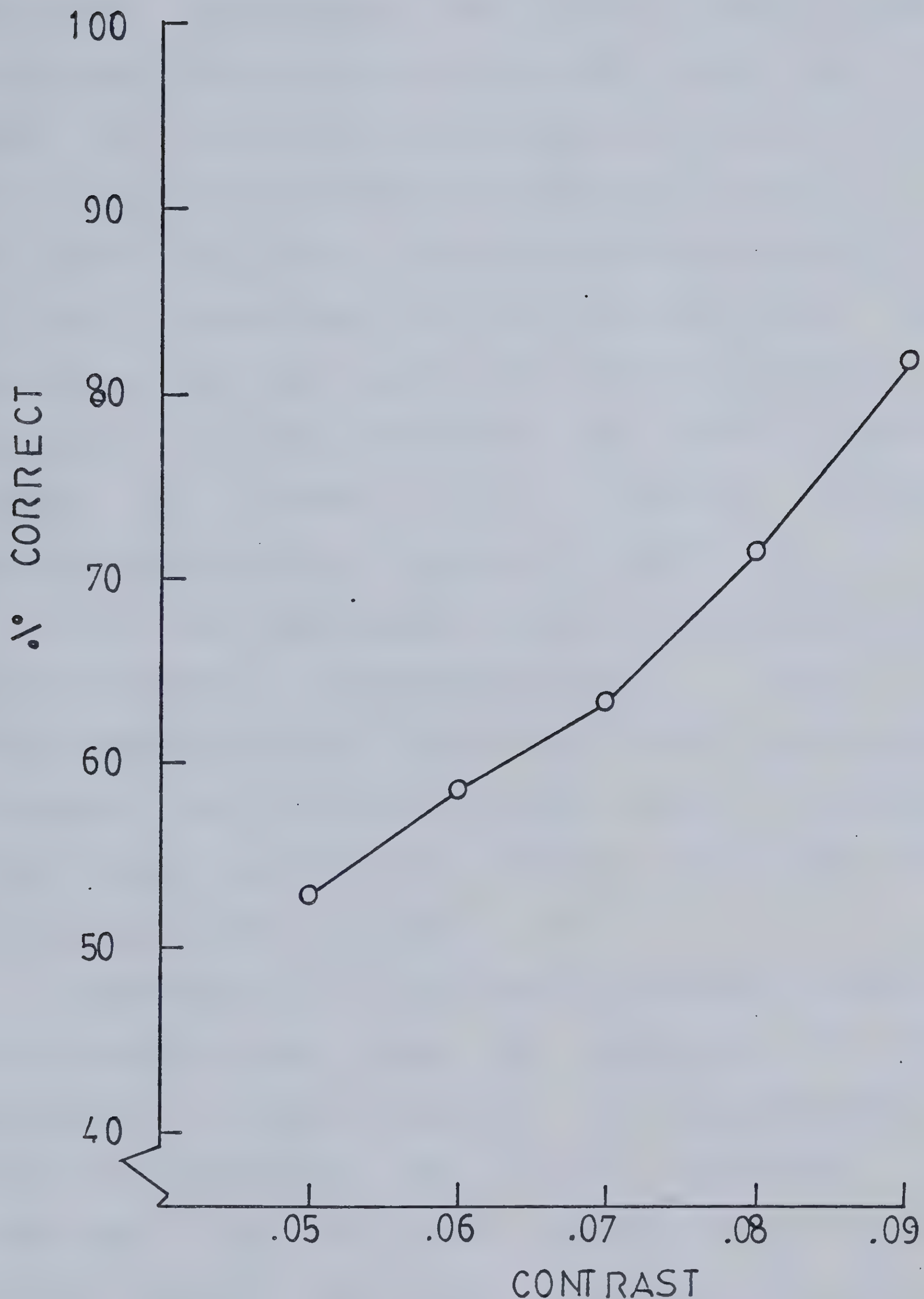
[3] This result appears to be the only one to be potentially affected by the loss of power resulting from the small number of subjects used in the experiment. In all other cases,the results were either strongly significant or equally strongly non significant.

Figure 5.Percentage of correct detection responses to single lines plotted as a function of contrast.Each data point has been obtained by averaging over 1,200 trials,in which two observers responded to individual lines displayed in all the orientations and positions shown in the second column of fig.2.


100
90
80
70
60
50
40
% CORRECT
.05
.06
.07
.08
.09
CONTRAST

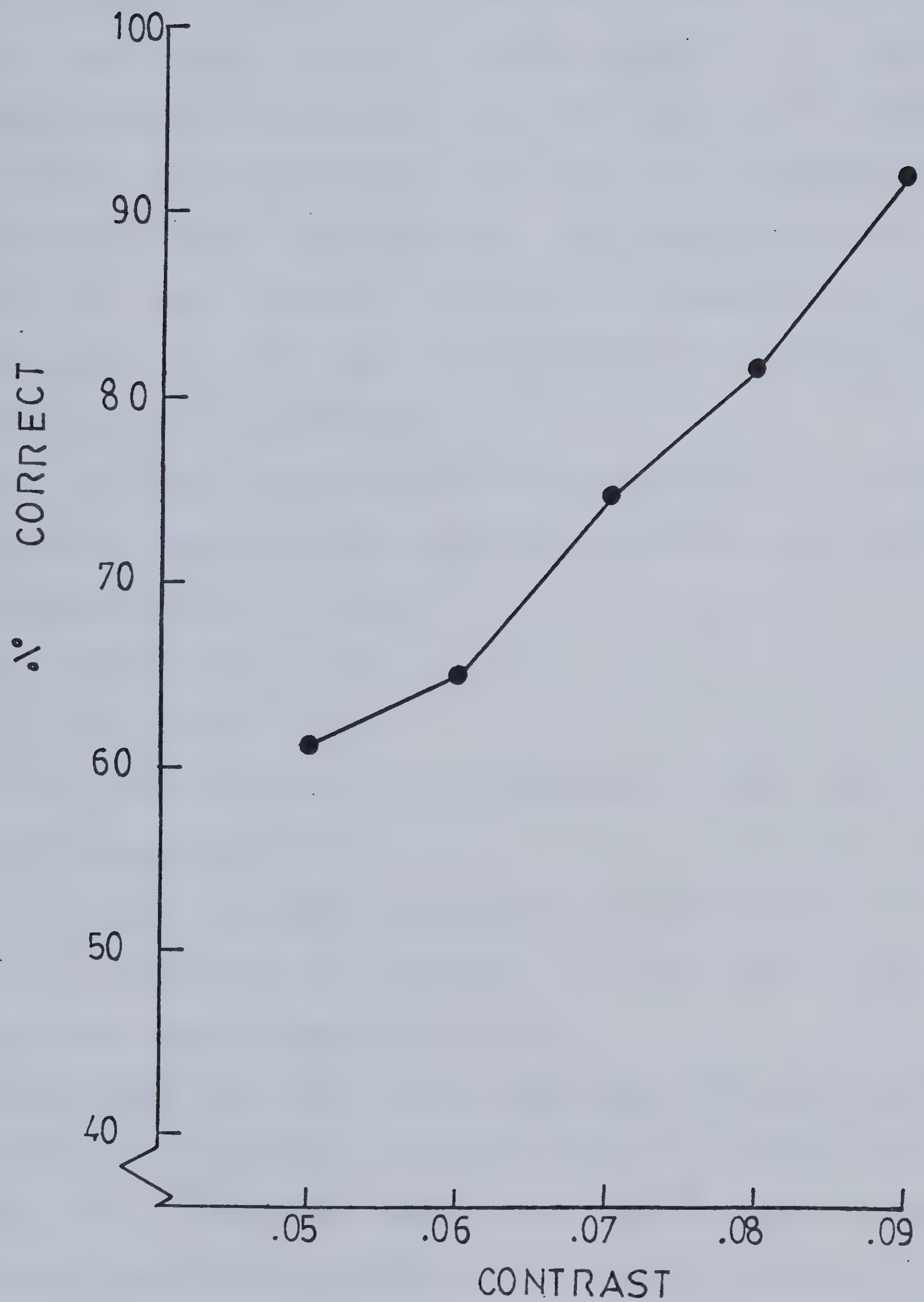
Individual vertical stimuli were detected better than horizontal ones,while oblique stimuli yielded the worst detection percentages ,the latter result being hardly surprising ,since this orientational anisotropia has been known for a long time (see Apelle,1972,for a review of the extensive literature about the "oblique effect").

The position factor was not significant.This is true both for the two positions in which right-positioned lines were presented as well as for the right/left position in which vertical lines were displayed (the latter condition was tested by means of a separate Subjects(2) X Position(left,right) X contrast(5) ANOVA).

The only significant effect in the case of two-line stimuli(average detection=74.9%) was contrast ($F(4,4)=49.28, p < 0.01$) (see Fig.6) While the position factor appeared to be irrelevant,a slight effect of orientation was found that replicated,on a smaller scale ,the anisotropias found in the case of single lines.

King-Smith and Kulikowski's expected probabilities of detecting two lines under the assumption of independent detection of each component line were computed. A slight modification,however, had to be introduced. In this experiment, the orientation and position of one of the two paired lines were varied.As a consequence,the probability of detection of each pair of lines had to be calculated by taking into account the specific probability (p) of a visual response associated to each of the two lines when presented

Figure 6.Percentage of correct detection responses to two lines plotted as a function of contrast.Each data point has been obtained by averaging over 1200 trials,in which two observers responded to the composite stimuli shown in figure 2.


100
90
80
70
60
50
40
% CORRECT
.05
.06
.07
.08
.09
CONTRAST

alone.In King-Smith and Kulikowski's experiment separated detection probabilities for each individual line were not calculated, since the lines were always vertical, parallel to each other, and it was assumed that their being positioned to the right or to the left of the center of the display area did not make any difference. In this experiment,the probability of detecting each two-line stimuli was deduced from the probability of a visual response (p) to each of the component stimuli by means of the following equations.

Let p_1 and p_2 represent the probabilities of a visual response to the components of a two-line stimulus,when the former are presented alone. Then:

$$p_1 = 2P(d/1)-1 \qquad \text{(Ia)}$$

$$p_2 = 2P(d/1)-1 \qquad \text{(Ib)}$$

A two line stimulus will be detected, under the assumption of independence, if

(i) There is a response to both lines (probability $p_1 X p_2$),or

(ii) there is a response to only one of the two lines (probability $p_1+p_2-2\, p_1 X p_2$),or

(iii)there is no visual response, but the subject guesses the correct interval (probability $1/2\ (1+p_1 X p_2-(p_1+p_2)$.

A little algebra shows that The overall probability of detection is thus: $P(d/2)= 1/2(1+p_1+p_2- p_1 X p_2)$ (II).

The predicted probabilities of detection for all two-line stimuli,at each contrast level,were thus calculated from equations (I) and (II).

The overall expected probability of detection of composite stimuli was obtained by summating all the expected probabilities for all such stimuli at all contrast levels and for both observers.The results were:obtained number of detection responses:74.9% (4495/6000);expected number 74.1% (4444/6000). Calculations were also carried out separately for each observer:for MMH,the observed overall detection percentage was 69.8,the expected 69.1.For the other subject, the observed overall detection percentage was 80,the predicted 79.1. Expected and observed detection probabilities were in closer agreement than in King-Smith and Kulikowski's study: they found observed and predicted probabilities of 74.4% and 76 % respectively..

Clearly,such a close overall fit between predictions and results cannot by itself be taken as conclusive evidence of the substantial validity of King-Smith and Kulikowski's model:large discrepancies of opposite sign between observed and predicted values might just produce an overall fit by cancelling each other out. Consequently,regression analyses were computed for each of the two stimuli at each contrast level. That is, for each two-line stimuli, the expected detection probabilities at each contrast level were plotted against the corresponding obtained detection probabilities,and the line of best fit was determined.
In order to increase the reliability of regression estimates (Harnett,1975), the latter was determined on the basis of the scores from both observers.

If King-Smith and Kulikowski's model is correct,then the expected detection probabilities for each stimulus at each contrast level should agree,within experimental error,with the corresponding detection probabilities. As a consequence,the best fitting line should have zero intercept and a slope of one.The null hypothesis that the slope of the regression line relating observed and expected values is equal to one was then tested against a two-sided alternative hypothesis by means of a t-test on the slope (Harnett,1975).A similar statistics was used as a test on the intercepts.

None of these tests produced significant results,thus suggesting that the differences in the spatial/configurational aspects of the two-line stimuli played no important part in their detection.

In order to investigate the presence of deviations from the model at a more molar level,Chi square tests for goodness of fit were performed for each stimulus at each contrast level,with subjects considered as independent replications of the same experiment (30 Chi square tests). Whenever several tests are carried out, the problem arises of how to set the error rate,the latter decision depending upon several factors (see, e.g.,Kirk,1968, and Myers,1979).The decision was made here to set alpha=0.01 for each individual comparison.This choice is consistent with the contemporary practice in the behavioral sciences for orthogonal comparisons(Kirk,1968,p.78),and with the growing

concern for Type two errors. A further motivation for setting the error rate independently for each comparison comes from the modest power-efficiency of Chi square tests.

Seven out of 30 tests were significant at the selected alpha level,thus revealing the presence of consistent "local" deviations from King-Smith and Kulikowski's model.

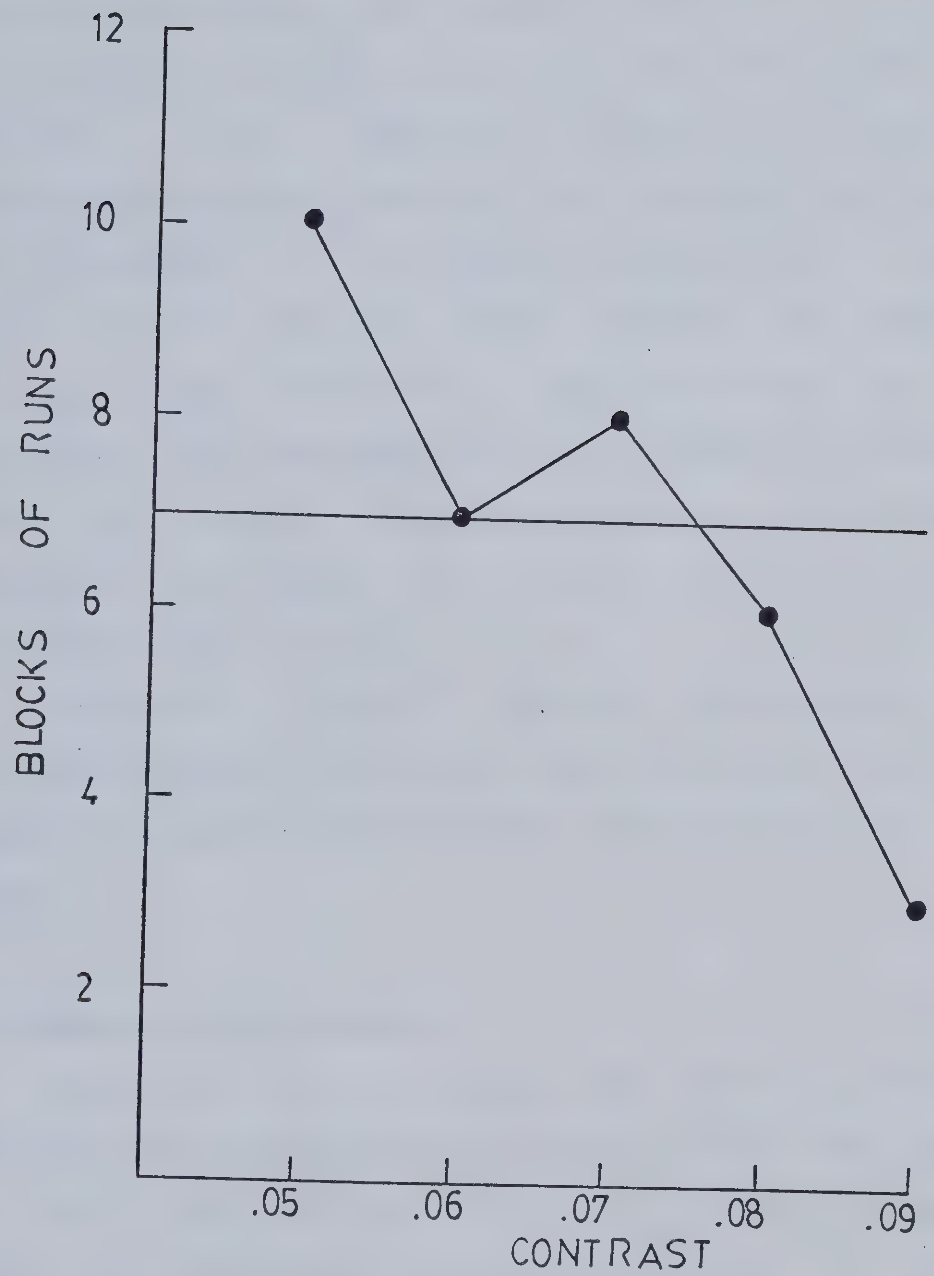
What about the direction of the deviations from the expected values? For both observers, in 17 out of the 30 blocks of runs (56.7%),the obtained detection probabilities exceeded the expected probabilities .

An interesting question is whether any trend occurred in the distribution of these deviations. It will be remembered that 6 two-line stimuli were presented at each of five contrast levels to two observers.Therefore,at each contrast level 12 blocks of 100 trials were used, and for each of these blocks expected and predicted probabilities were determined. In Fig.7,the number of block of trials in which the observed probabilities exceeded the expected probabilities is plotted as a function of contrast.

Overall,a positive deviation from the predictions was observed in 34 out of 60 blocks of trials (56.7%).

The solid horizontal line in Fig.7 represents the theoretical distribution of positive deviations from the model under the assumption of independence from contrast. The actual distributions of these deviations is quite

figure 7. Theoretical (horizontal solid line) and actual (filled circles) distributions of the positive deviations from the expected detection probabilities for two-line stimuli calculated from King-Smith and Kulikowski's model.The abscissa represents contrast,and the ordinate the number of blocks of 100 trials that the two observers completed by responding to all the composite stimuli.


12
10
8
6
4
2
BLOCKS OF RUNS
.05
.06
.07
.08
.09
CONTRAST

different:at the lowest contrast levels positive deviations from the predictions outnumbered the negative ones,and the opposite occurred at near treshold levels.

An Anova carried out over the differences between observed and expected results (factors of subjects,orientation,position, and contrast) amply confirmed the existence of a sizable effect due to luminance ($F=34.17, p<0.01$);no other effect reached significance.

Additional differences were noted.The size of the deviations from the predictions was greater for some stimuli than for others (see fig.8,9,and 10),neither the distribution of positive and negative deviations was always consistent (see Fig.11).

However,no clearly defined relationship between stimulus contrast and spatial characteristics of the stimuli beyond the general trend already discussed (Fig.12) could be seen.

D. Summary of the results

Averaging over contrast, the observed probability of detection of two-line stimuli spaced 30 min was found to be in very close agreement with the predictions based upon a model that postulates independent detection of the single lines;in even closer agreement, in fact,than in the case of King-Smith and Kulikowski's experiment (1981).

The influences of the spatial variables were not strong enough to yield significant deviations from the predictions

Figure 8. Comparison of the observed and expected probability-of-seeing-curves for composite stimulus A. Observer:GM.

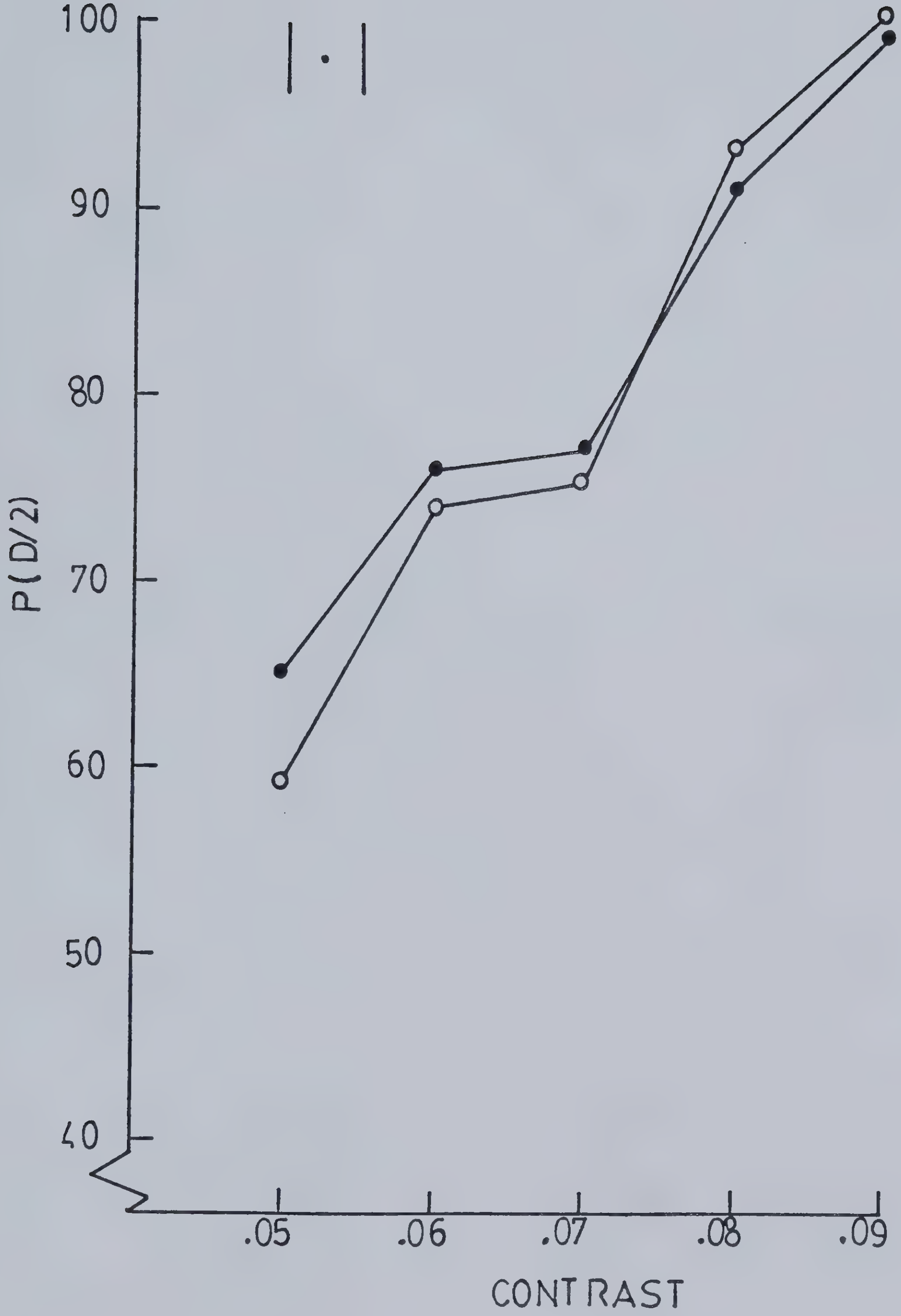
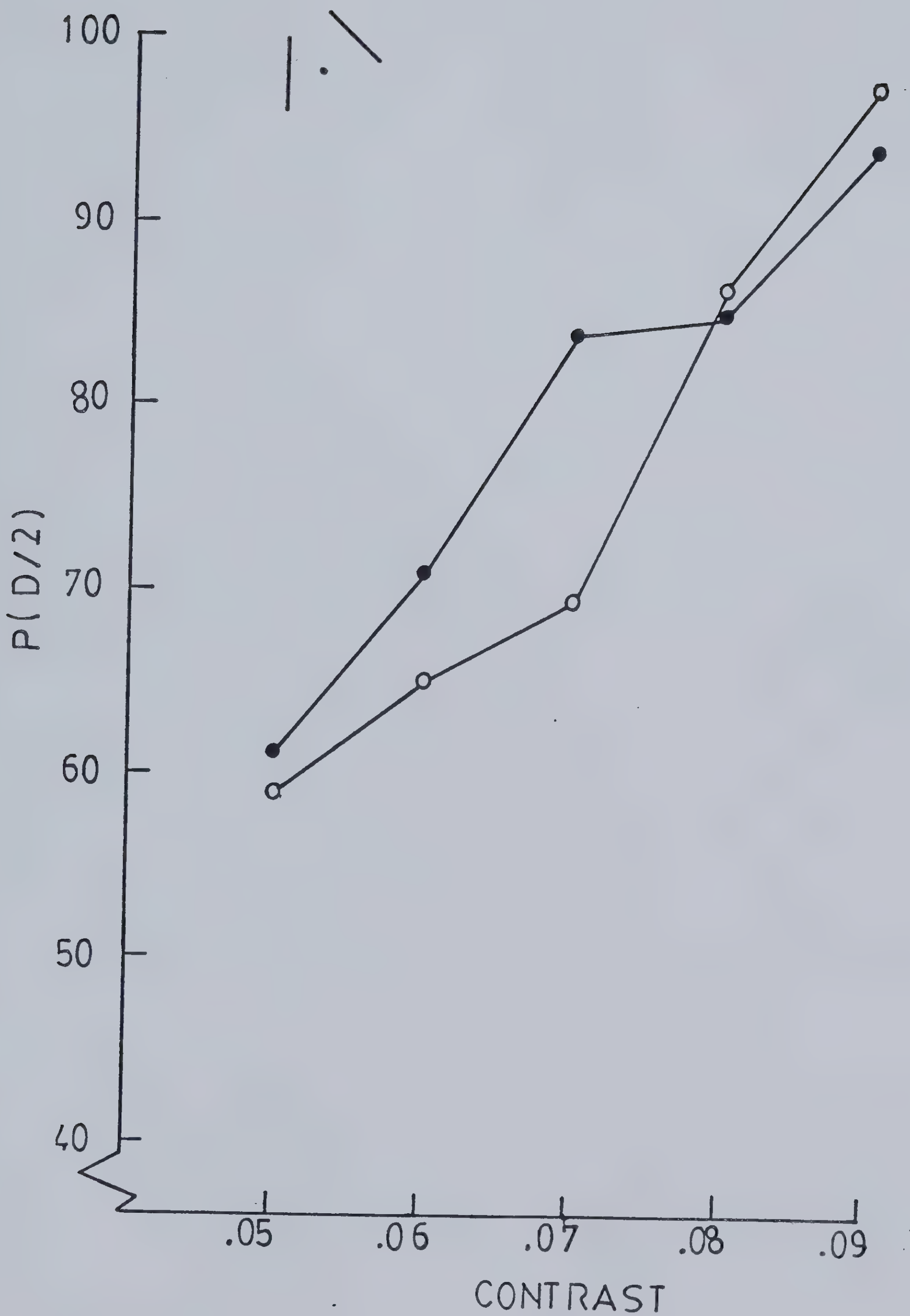
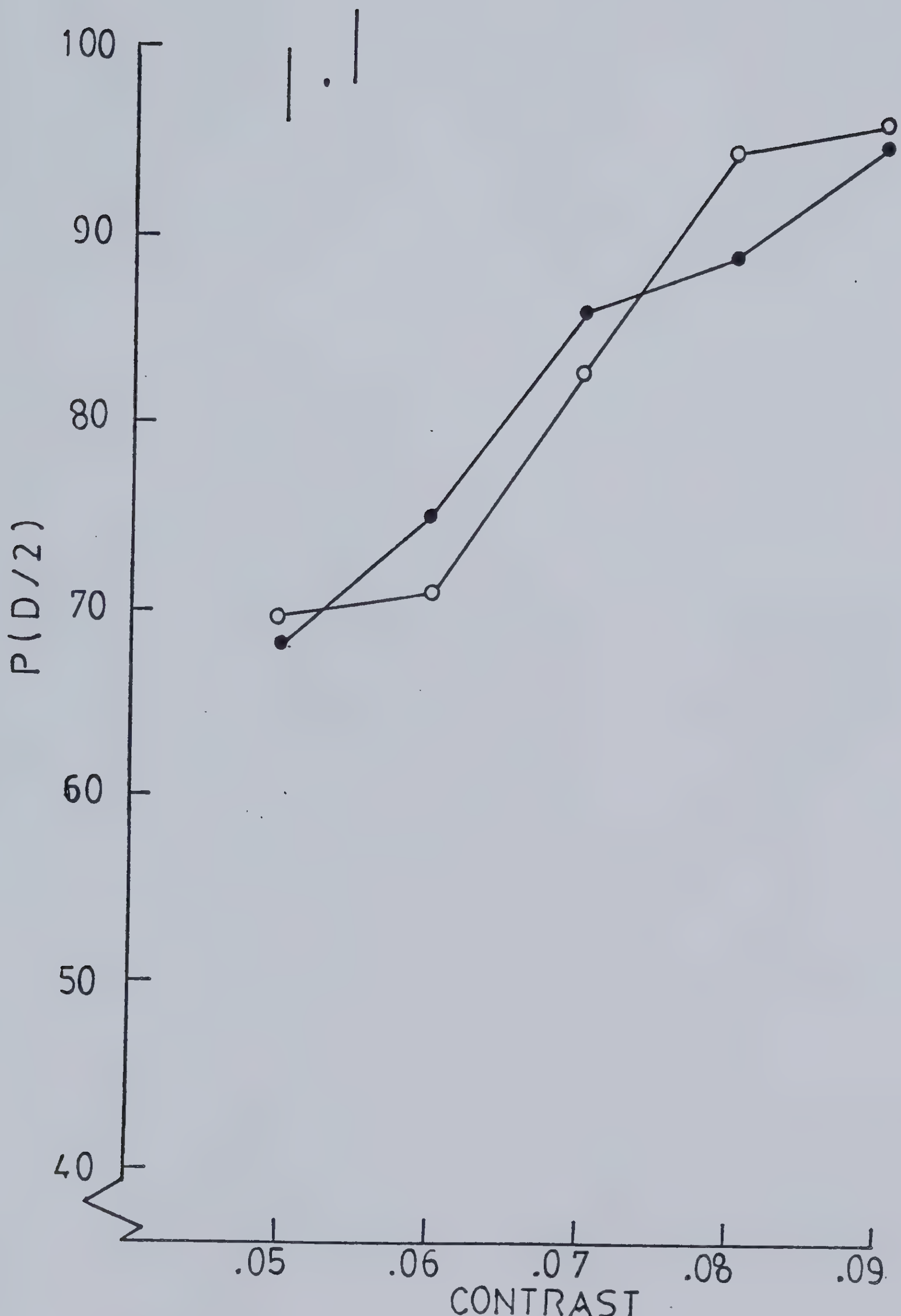

100
90
80
70
60
50
40
P(D/2)
.05
.06
.07
.08
.09
CONTRAST

Figure 9. Comparison of the observed and expected probabiliyt-of-seeing curves for composite stimulus D. Observer:GM.



100
90
80
70
60
50
40
P(D/2)
.05
.06
.07
.08
.09
CONTRAST

Figure 10. Comparison of the observed and expected probability of seeing curves for composite stimulus B. Observer:GM.



100
90
80
70
60
50
40
P(D/2)
.05
.06
.07
.08
.09
CONTRAST

Figure 11. Comparison of the observed and expected probability-of-seeing curves for composite stimulus F. Observer:GM.

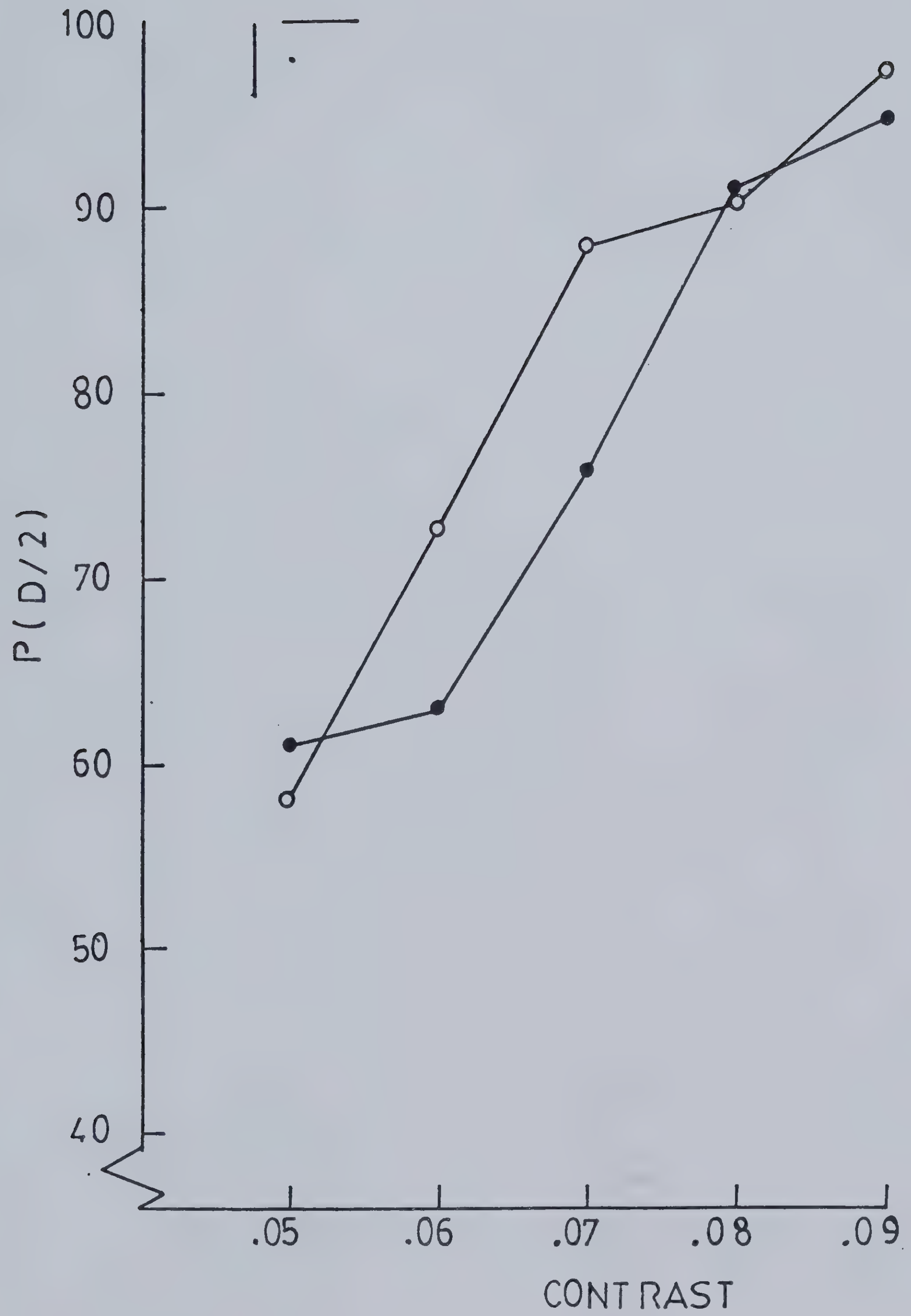
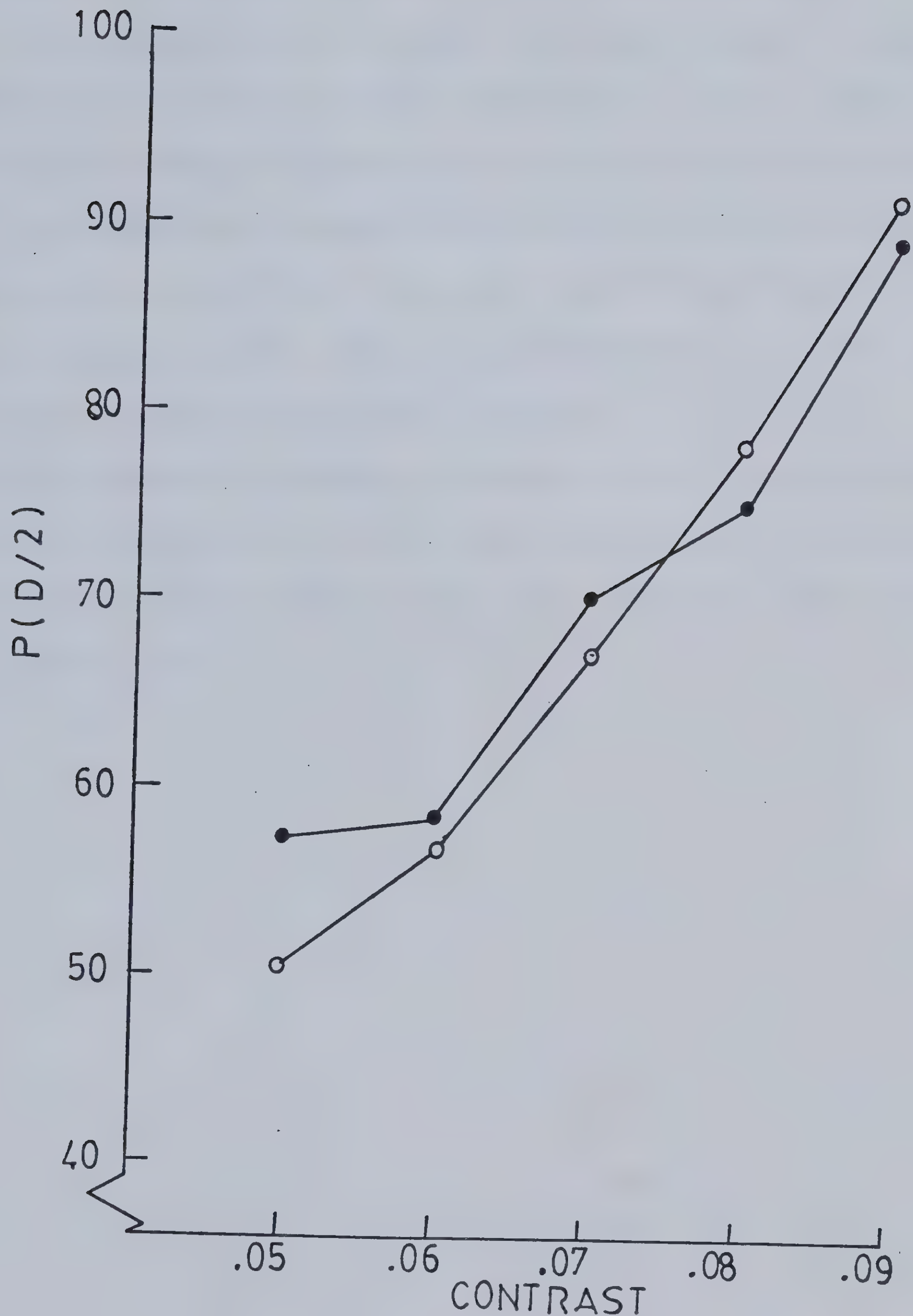

100
90
80
70
60
50
40
P(D/2)
.05
.06
.07
.08
.09
CONTRAST

Figure 12.Observed and expected probability of-seeing curves for observer MMH,obtained by averaging over all double stimuli.



100
90
80
70
60
50
40
P(D/2)
.05
.06
.07
.08
.09
CONTRAST

based upon the assumption of independence.

Deviations from King-Smith and Kulikowski's model, however, emerged when the focus of the analysis was brought to bear upon the effects of contrast. Chi square tests revealed the presence of consistent deviations at a more molar level across all stimulus types and contrast levels.An analysis of the distribution of these deviations revealed that for both observers at the lower contrast levels the observed results were sizeably higher than expected,while at the highest contrast levels the opposite occurred.

Thus the apparent agreement between predictions and data on averages turned out to be due to systematic deviations of opposite direction determined by contrast and cancelling each other out.

III. DISCUSSION OF THE RESULTS.

A. A comparison of results.

Any attempt to account for the results of this experiment must consider two main findings: a) that the detection of two-line stimuli appeared to be not affected by the spatial characteristics of the stimuli used (orientation,position); b) that the detectability of these same stimuli was generally lower than expected at low contrast levels,and generally higher than expected at high contrast levels.

The latter result is not incompatible with the close agreement between predictions and data averages reported by King-Smith and Kulikowski (1981).
These authors also proceeded to an analysis of their data as a function of contrast. They did not do so,however,by means of a straighforward application of their basic detection model,as it has been done here.Rather, they accomplished their analysis within the context of their model for detection-and-recognition of composite stimuli.

The analyses they performed thus involved complex averaging procedures among the data from various experiments,and equally complex assumptions were involved in the determination of the expected probabilities (see King-Smith and Kulikowski,1981,p.242 ff). For example, the detection probabilities estimates were obtained indirectly,by pooling data from the

detection-and-recognition of two-line stimuli (which underestimated the results) and the detection-without recognition of two line stimuli (which overestimated the results).

Consequently, no independent assessment of the fit between observed and expected detection probabilities as a function of contrast in terms of their basic detection model was carried out.

In an earlier study, King-Smith and Kulikowski (1975) analyzed detection of composite stimuli in terms of an algorithm based upon the notion of probability summation that was substantially similar to the basic model employed in their later study.

Their findings about the detection of two-line stimuli spaced 15 min apart were found to be compatible with probability summation. They did not,however,excluded the possibility of facilitatory interactions between the stimuli.In fact, the probability of seeing curves for two lines presented in that paper (fig.1a,p.242) reveals that, at contrast levels which yielded detection percentages in the 50-80% range, consistent deviations in excess from their model were observed.

Very similar results in the same contrast range were found by comparing the probability of seeing a rectangular grating with 15 min periods with the probability of seeing two rectangular gratings of 30 min period which were interlaced together to form the 15min period grating (King-Smith and

Kulikowski,1975,fig.3).
When they compared the visibility of a rectangular grating with the visibility of the composing lines, they again found that,particularly for lines spaced 15 and 30 min, contrast levels yielding detection percentages in the 50-80% range often produced positive deviations from the assumption of independence (King-Smith and Kulikowski,1975,fig.4). It thus appears that these results are quite similar to those obtained in the experiment here presented. As fig.14 shows,the positive deviations from the model occurred at contrast level yielding detection percentages around the 50-75% range.Furthermore,small negative deviations from the model at the highest contrast levels also occurred in King-Smith and Kulikowski's earlier study (1975).

B. False positives,bidetectors,variations in sensitivity?

In their 1981 study, the observed probabilities of detecting-and-recognizing composite stimuli were higher than expected. King-Smith and Kulikowski consequently introduced some modifications in their model to account for the observed discrepancies.

First,they noted that their basic model implies the existence of "high threshold" processes. Their model assumes, in other words,that the line detecting mechanisms have sufficiently high thresholds to prevent transmission of "visual noise" to a significant degree.

Problems with this assumption have been repeatedly noted (see,e.g.,Swets,1961,and Krantz,1969), and general psychophysical evidencence (ibid.) seems to be more consistent with the notion of lower threshold processes which allow the occasional transmission of noise bursts. if this is true,then increased false positives should occur,and so affect the independent-detection model in the following ways.

It will be remembered that,according to the model,the observed detection of a single line is supposed to be the outcome of two mutually exclusive events:the probability of a visual response (p),and the probability of a correct guess.The estimation of p,which will enter into the determination of the expected probabilities of detection of two-line stimuli,is thus inferred from the observed detection probabilities of a single line after correcting for guesses.

The above assumption implies that, when there is no response from a line detecting mechanism,the occurrence of a response from an unstimulated detector will have a similar effect to guesses.When,however,there is a response from a stimulated detector,the influence of a false positive will have a different effect on the detection response depending upon the temporal occurrence of the latter event. If a false positive occurs in the same interval in which the stimulus is displayed and is responded to by the stimulated detector,the former event should have no effect on the

detection response, since,by definition,a stimulus is detected whenever a response from a line detector occurs. If,however,the false positive occurs in the interval other from the one in which the stimulus is presented and responded to,then the detection response is reduced to guessing, despite the presence of a response from a line detecting mechanism.

As a consequence, the estimation of p by means of the basic independent detection model may lead to an underestimation of the actual probabilities of a visual response. Since these probabilities enter into the determination of the predicted detection probabilities for two line stimuli, the uncorrected model would lead to an underestimation of the latter.

Could such a modification,if introduced in the model, better account for the data obtained in this experiment?

The answer is negative. Greater p values,in fact,by leading to greater E(P d/2),could provide a better fit for the data from the lowest contrast levels. At the highest contrast levels, where the observed detection values were lower than expected,these greater values would further increment the observed discrepancies.

The correct detection of two-line stimuli, according to the basic model,is due to visual responses to both lines or to one line only (and to guesses).It is plausible to assume that the relative weight of these components in the process of detection of two-line stimuli varies as a function of

contrast. It might be argued,then,that at low contrast levels more one-line than two-line responses from stimulated detectors occur,while at high contrast levels the occurrence of visual responses to both stimuli should increase. The latter event would correspondingly decrease the effect of false positives on detection.Thus, at the highest contrast levels, no increase in the expected detection probabilities would have to be introduced.Even this consideration,however, cannot account for the negative deviations from the model observed at the highest contrast levels. In conclusion,it seems that no satisfactory account of the data of the present experiment can be achieved by the consideration of false positives.

King-Smith and Kulikowski (1981) proposed a second modification to their basic detection-and-recognition model. They suggest that,in addition to the localised detectors postulated by their basic model,the possibility should be taken into account of detectors responding to both lines (or "bidetectors").

Besides the obvious ad hoc nature of this hypothesis,it is also clear that this modification cannot account for the findings of the present experiment.
This is the case because the response from bidetectors would increase the expected probabilities of detection especially at the highest contrast levels (see King-Smith and Kulikowski,1981, fig.6 and 7).

Finally, an overall decrease in the expected detection probabilities in comparison with the predictions from their basic detection model was achieved by king-Smith and Kulikowski by considering the possible effects of general variations of visual sensitivity from trial to trial.
This modification cannot satisfactorily account for our findings, since it does not consider contrast modulating effects.
For the above considerations, it seems plausible to conclude that the modification to their basic independent detection model proposed by King-Smith and Kulikowski(1981) to account for the deviations from the predictions based upon the assumption of independent detection of composite stimuli can hardly account for the findings of this experiment.

C. Probability summation and spatial interactions

Indeed, King-Smith and Kulikowski (1981,p.248) acknowledged that, were the hypothesis of spatial interactions taken into account, a good fit for data otherwise deviating from the basic independent detection model could be achieved. These modifications, however, would seem to have a different impact upon the model than the others previously considered.

In fact, once the hypothesis of independence and the additional assumption of spatial interactions were combined, the uncomfortable conclusion would have to be reached that the model assumes the independent functioning

of non independent detectors,or that there are independent line detectors which are not independent line detectors !

In an earlier paper,King-Smith and Kulikowski exemplified this approach:

> "We can explain about 75-80% of the increased sensitivity to a grating relative a to a line from probability summation from the detectors responding to individual component of the grating; the remaining 20-25% of the improvement may correspond to some facilitatory interactions between the detectors responding to the different components, e.g. disinhibition."(1975,p.248)

Similar assertions,it seems, acquire significance by taking into account the problem they are addressing: whether the detection of composite stimuli such as rectangular gratings should be explained by assuming the existence of sharply tuned grating detectors,or whether more broadly tuned line detectors acting together could achieve the same end.

The calculations based upon the notion of probability summation can therefore be properly used as a guideline against which to test the former hypothesis. Small deviations from the predictions can then reasonably accounted for by maintaining the basic assumption about the detection of composite stimuli by means of localized units at different spatial positions.

The latter approach,however,does not require the assumption of independence. And this assumption cannot be combined with that of interaction without running into a contradiction.As a consequence,whenever the additional hypothesis of spatial interactions is resorted to to account for experimental findings,the notion of independence should be rejected.

All that is needed, is that the detection of composite stimuli be achieved by means of different localized units at different spatial positions acting simultaneously in the detection process.

If the preceeding analysis is correct, it follows that even a close fit between predictions from probability summation based algorithms does not necessarily implies a true independence between visual detectors.

Rather,this fit should be interpreted as reflecting a particular state of activity along the continuum of interactive processes among visual elements bounded at the opposite ends by the emergence of inhibition and facilitation.

This approach is consistent with formulations of the functioning of visual detectors that are generally representable by by equations of the form :

$$\phi_i = \eta_i + \sum_j C_{ij} R_j$$

where (ϕ_i) is the output of cell i, (η_i) is the external input to cell i, Rj is the averaging firing rate of cell j,and Cij

is the connectivity matrix between cells i and j representing complex dendritic processes between the cells (see Leake and Anninos, 1976,Sejnowski,1976,Caelli et al,1978, Caelli,1981).

This type of formulation implies that the response of a cell is always jointly determined by a retinotopic component (η_i) and by its connections with the functioning of other cells (a positive Cij corresponds to excitatory gains, while a negative Cij corresponds to inhibitory gains).

The latter component was unformally commented upon early by Hubel:

> "A single cell may receive several excitatory and inhibitory impulses at once,with the result that it will respond according to the net effect of these inputs."(1963,p.151)

It is possible that the agreement between probability summation and data could evolve from conditions of equilibrium between (psychophysically defined)detectors, which are not due to independent functioning of these units,but,rather, to the outcome of complex weightings of excitatory and inhibitory gains among these units.

The deviations from "independence" would then correspond to the breaking down of equilibrium conditions as a function of changes in the input to these units which would alter the overall value of Cij.

D. Inhibition and facilitation.

"Mach was the first to suggest that mutual interactions among the elements of the retinal network in the retina were responsible for the maxima and the minima in the subjective appearance of an edge.He supposed that the response of a single receptive unit of the retina was determined in part by the luminance of the light impinging on it,and in part by the signals sent from neighboring cells to that unit.Mach's mathematical model can be interpreted in terms of excitatory and inhibitory components,in which the inhibitory effects are assumed to increase both with the stimulus luminance to the inhibiting cell and to decrease with increasing distance betwen the interacting cells.The inhibitory effects of different cells on the same units are supposed to summate, and the response of the first element to be related to the sum of the inhibitory influences ...Several other models have been proposed more recently,each of which accounts for the Mach phenomenon at least in some respects... All the theoretical formulations can be ultimately reduced to the following basic assumption:the function that describes the response of each element of the neural network has an excitatory component,which depends on the luminance of the stimulus to that element,and an inhibitory

> component, that depends on the luminance of the stimuli to the surrounding elements and on the distance of each of them from the first element" (Fiorentini,1977,p.197-198).

(See Ratliff,1965, for a discussion of various theoretical accounts of Mach's bands).

The above quotation is relevant to the current discussion for a number of reasons. It first shows that the interpretation of the response of visual elements in terms of network models is neither recent nor solely due to the influence of cybernetics (see,e.g.,Dodwell,1970).
It also exemplifies the predominant role assigned until recently to inhibitory gains in the determination of the value of Cij,the connectivity matrix indexing the communication factor between the units constitutive of the network.
Finally,it contains suggestions of value for the interpretation of the results of the present experiment.

Mach's model,in fact,predicts that the strength of lateral inhibition between neighboring units is a function of luminance;more precisely, it predicts that "Lateral inhibition is strongest or weakest at points where the second derivative of the retinal illumination is maximal or minimal" (Fiorentini,1977,p.197).The absolute threshold for the occurrence of Mach's bands is thus taken to correspond to the level at which the inhibitory component of the detecting unit is reduced or ineffective.

This important relation between luminance and strength of inhibition seems to be of general validity (see Haber and Hershenson,1978),and the latter can be brought to bear upon the results of this experiment.It seems reasonable to assume that the negative deviations from the predicitions observed in this experiment correspond to the building up of increasingly strong lateral inhibition between the line detectors at the highest luminance levels.

Before commenting in greater detail about this conjecture, it may be asked whether the latter can account, by itself, for all the results of the experiment. The answer is negative.

By correcting the basic detection model for inhibition as a function of luminance,in fact, only the negative deviations from the former at the highest luminance levels would be accounted for,not the deviations in excess from the model observed at the lowest luminance levels.

It thus appears that,if the results of the present experiment are to be explained in terms of spatial interactions among line detecting mechanisms,a more general interpretation of the connectivity matrix would have to be accepted which includes not only inhibitory,but also excitatory gains.

The point where the observed and expected probability of seeing curves meet,might then be interpreted as corresponding to a condition of equilibrium between excitatory and inhibitory gains between the line detecting

mechanisms,resembling a condition of independence.

At the highest luminance levels,the inhibitory component would become predominant,while at the lowest luminance levels,where inhibition is very weak, facilitatory gains woul play a predominant role,the latter assumption been also consistent with neurophysiological measures suggesting that facilitatory synapses have a lower treshold than inhibitory ones (Haber and Hershenson,1978).

What is the nature of these facilitatory interactions?The most parsimonious assumption to account for the results of this experiment is to postulate the occurrence of direct facilitation between line detecting mechanisms of similar type.

According to this hypothesis, the stimulation of a line detector may lead to the lowering of the treshold for similar surroundings detectors.

By not taking into account this possibility, King-Smith and Kulikowski's basic independent detection model (1981) would lead to an underestimation of the detection probabilities for two line stimuli at low levels of luminance.

Some direct psycophysical evidence for the above hypothesis is available.

In 1973,King-Smith and Kulikowski found that the visibility of a test line was not improved by placing two subtreshold lines 12 min on either side of it.When,however,the two lines were just supratreshold,the test line treshold contrast was

lowered. A direct facilitation between nearby line detectors was suggested as a more plausible explanation of these findings than the hypothesis of disinhibition within a line detector.

As noted before,the hypothesis of facilitation between detecting mechanisms was also resorted to by King-Smith and Kulikowski (1975) to account for deviations in excess from their probability summation based detection model for two line stimuli,multiple line stimuli,and rectangular gratings. The existence of distal facilitation was clearly demonstrated by Hilz and Rentschler (1975).In that study,it was shown that,while the detection of a line may be even inhibited by too bright inducing lines,at intermediate intensities the inducing line has a facilitatory effect on the test line. Beitel (1936) obtained comparable results with square shaped stimuli.

In agreement with the interpretation of the response characteristics of line detectors previously presented, Rentschler and Hilz (1976) also found evidence,within the subthreshold summation paradigm,that facilitation determined by the inducing lines is in fact the net outcome of both facilitation and inhibition.

Interactions between lines with up to 2.4 degree of separation are reported by Swantson (1981).He utilized the fact that steadily fixated lines, under certain conditions,undergo periodic disappearances (resembling,as MacKinnon et al. showed in 1979,the visibility cycles of

afterimages and optically stabilized images) to determine how the visibility of a steadily fixated bright vertical line was modified by the presence,separation and distance,of a likely oriented line displayed together with the test line.

The disappearance of the test line was found to be markedly reduced by the presence of the second line at separations of .8 and 2.4 degree (no other separations were investigated). The stabilization of the test lne,however,only occurred when the second line was displayed at the same luminance as the test line:no such stabilizations occured when the inducing line was either brighter or dimmer than the test line.

All of the above findings clearly point to the critical effect that luminance seems to have in determining nature and extent of lateral interactions in visual phenomena,effects that combine in complex ways with distance.

Findings like those of Rentschler and Hilz (1976)in which the distance where facilitatory interactions occur was found to be smaller for higher luminances, suggest that the effects of the former should not be considered independently from the latter's.

This appears to be the case also with respect to the interpretation of the nature of facilitatory interactions. An example of this is provided by Rentschler and Hilz (1976).They showed that evidence of facilitatory interactions due to subtreshold inducing lines is amenable

to an explanation in terms of disinhibition within a line detecting mechanism.Facilitatory effects induced by just supratreshold induce lines make more plausible,instead,the hypothesis of facilitation between detectors.

The experimental conditions arranged in the present experiment are,both in terms of luminance and distance,more compatible with the latter hypothesis.

E. Spatial interactions and stimulus properties.

To this stage,no analysis of the role of spatial variables (orientation/position)in the experiment has been presented.

The reason for this is simple: no significant effects were found.

Possibly, the set of values of the spatial variable used in the experiment were not extreme extreme enough to allow the emergence of such a relationship.

While this may well be the case,the present findings force the conclusion that, insofar as the deviations from the assumption of independence here reported are attributable to lateral interactions between line detectors, these interactions were not orientation/position specific.This conclusion,in its turn,suggests two possible reasons for these findings.

First,it might be suggested that these interactions occurred at the lower levels of the visual system (retina,LGN),which do not code for spatial characteristics

of the stimuli such as orientation.

This suggestion is also consistent with an argument by Glezer et al.(1977) which,commenting upon the requirements of detection tasks which simply require to signal the appearance of stimuli,claimed that the observer's responses could be made on the basis of signals from the lower stations of the visual system.

While this suggestion cannot be discounted,two related observations place some constraints upon its validity. First,at the highest luminance levels,the orientation of the stimuli was clearly perceived;second, a significant orientation effect was found for one-line stimuli:both these findings,thus,clearly point to at least an involvement of orientation detectors in detection tasks.

If this second assumption is to be favored, however,it remains unexplained why no orientation specific interactions emerged.To rephrase this question: does it follow,from the fact that interactions occur among orientation detectors,that these interactions must be orientational?

The answer is negative.Of course,orientation specific interactions would help to prove that their origin is intracortical,and in fact a number of psychophysical studies aimed at this problem proved with various success that orientation specific interactions do indeed occurr (see,e.g.,Bakemore and Carpenter,1973; Kulikowski and King-Smith,1973;Rentschler and Fiorentini,1974).

The search for interactive events among cortical cells has also been extensively pursued with neuphysiological methods(Blakemore,et al.,1970;Jones,1970; Benevento,Creutzfeld and Kuhnt,1972; Bishop,Coombs,and Henry,1971,1973; Blakemore and Tobin,1972; Creutzfeld,Innocenti and Brooks,1974;Creutzfeld,Kuhn,and Benevento, 1974;Henry,Dreher and Bishop,1974;Hess, Negishi,and Creutzfeld,1975;Maffei and Fiorentini,1976; Nelson and Frost,1978).

The method generally followed in these investigations consisted of recording the response of individual cells in area 17 and 18 of the cat visual cortex to moving optimal stimuli (bars,edges,etc.)so as to determine extent and characteristics of their receptive fields. The responsiveness of this same cell while a second stimulus not stimulating their receptive field was simultaneously displayed was then determined.

All of the above mentioned study were able to prove the presence of powerful interactive phenomena. These effects were found to occurr in most cells, and were found to be mostly inhibitory for some cells, mostly facilitatory for others,and a combination of the two for still others.
Inhibitory interactions appeared to be non orientation specific (Maffei and Fiorentini,1976), or due to both orientation specific and non specific inhibitory input (Nelson and Frost,1978).
Facilitatory interactions were sometimes found to be more

orientation specific than inhibitory ones (see e.g Blakemore and Tobin,1972, and Maffei and Fiorentini,1976);but more data are needed before any conclusion can be reached on this issue (see Nelson and Frost,1978).

Importantly,Maffei and Fiorentini (1976) failed to find any evidence about the existence of either facilitatory or inhibitory regions extending beyond the classic receptive field area of lateral geniculate cells.

The above findings should make clear the following point:while the absence of orientation specific interactions does not require to assume that the latter occurred among peripheral units,the assumption of spatial interactions among orientation detectors does not require that the latter be orientational in nature.

It is thus felt that the latter hypothesis can be endorsed in this context for the reasons previously mentioned.

An attempt to account for the findings of the present experiment on the basis of spatial interactions among visual detectors is thus consistent with electrophysiological findings which point to the existence of strong facilitatory and inhibitory events occurring among cortical detectors and mainly built in within the cortex. The additional assumption that is required is that facilitatory interactions may be proportionally strongest,and inhibitory interactions weakest,at low luminance levels, while the opposite occurs at high luminances. This assumption has not been tested in

the previously mentioned studies ,and should indeed be.As noted before,however, the latter is fully compatible with what is generally known about the different temporal and energy requirements for the building up of facilitation and inhibition.

IV. CONCLUSION

In this experiment, the probability of seeing individual lines as a function of contrast was first determined.

Next,the probability of seeing two lines was obtained.The two lines were positioned at a distance (30 min) that,according to a well-substantiated body of psychophysical evidence, ensured that the two lines would fall within the perceptive field of two different line detectors.

It was then determined how well the detection probabilities of these two line stimuli was accounted for in terms of the probabilistical sum of the detection values for each line.

The results indicated that, at low contrast levels, the observed values were higher than expected,while the opposite trend was observed for the highest contrast levels. These results were not appreciably affected by spatial characteristics of the stimuli such as orientation and position.

It was shown that auxiliary assumptions such as those proposed by King-Smith and Kulikowski (1981) could not satisfactorily account for the results of this experiment.

Instead,the hypothesis of luminance dependent spatial interactions among line detectors was found to be compatible with the results, as well as with a substantial body of neurophysiological evidence.

An important question,remains: While the assumption of neural interactions may be considered sufficient to explain the results of this experiment,is it also necessary?

While no sharp answer can be provided to this question,the way in which the latter may be related to an important issue in vision research should be considered. The issue is,quite simply:what is a "receptive field?"

> "We have reported that around the receptive field of the simple and complex cells of the striate cortex,there exist regions that although unresponsive to moving or flashing bars when stimulated in isolation have dramatic effects on the cell responsiveness.The effects on the unresponsive regions can be either facilitatory or inhibitory...The inhibitory unresponsive regions,when suitably stimulated, can be so effective as to suppress or drastically decrease the cell's response to an appropriate stimulation of its receptive field."(Maffei and Fiorentini,1976,p.1138)

The above quotation reflects,in my opinion, the problematicity surrounding the notion of "receptive field".It clearly points to the fact that the characterization of receptive fields is a function of the methodology used,which,in turn,reflect the epistemological options of a given research paradigm.

A clear presentation of the approach constitutive of this paradigm was provided by the De Valois' (see

Introduction,p.2).
The understanding of how the visual system recognizes visual scenes,according to this approach,first and foremost requires the identification of the "discrete subunits" that analyze the scene "by responding only to certain attributes of the pattern which occur within a delimited area of the visual field".

The single cell recording methodology,andt its psychophysical equivalents,seem to reflect the atomistic approach.
The ideas underlying the development of the notion of probability summation are consistent with this approach:upon identification of the discrete subunits that the visual system is made of,the next step is to calculate how they summate with each other.A further step is to explain the deviations from this model.While general properties of the visual system (variations in sensitivity,treshold fluctuations etc.) seem to be preferred,assumptions in terms of lateral interactions between detectors are also acceptable,particularly when their effect is simply to enhance or decrease the responsiveness of visual detetors without altering the fixed perceptive field organization previously determined.

In this experiment,by choosing to evaluate its results in terms of probability summation, the conclusions that could be reached were obviously constrained by all the assumptions implicit in the design of the experiment.

The particular solution proposed seems warranted by the results better than others;thus,in a weak sense, the former is "necessary".

Maffei and Fiorentini's (1976) "Unresponsive regions [that] have dramatic influence on the cell responsiveness" (1976,p.1131),on the other hand,reflect some of the difficulties and ambiguities that are affecting the atomistic approach,and point to the need for a drastical revision of time honored notions.

Again,Maffei and Fiorentini (1976) offer a good example of this:

> "All the cells we analyzed were within 5 degree of the area centralis.In this part of the visual field the inhibitory and facilitatory unresponsive regions were at least three times as large as the receptive field, and their influence on the cell response and on its properties of response were surprisingly rigorous.In the light of this evidence we fear that the classical concept of receptive field should be revised. This concept can suggest the misleading idea that individual visual cells at the various levels of the visual pathway elaborate certain charactheristics of the visual stimulus in isolation.On the contrary, as the evidence already suggests at the retinal level (McIlwain,1964,1966),and even more so in the cortex an assembly of cells might work together for the

analysis of a relatively large region (5-10 deg) of visual space.The concept of a hypercolumn recently put forward by Hubel and Wiesel (1974,a,b) strengthens this hypothesis.The model in which cortical receptive fields are built up from geniculate ones in a sort of geometrical way are certainly attractive because of their simplicity.One can get excited in learning how simple the organization of the central nervous system can be.Their usefulness is not disputed provided that they do not sidetrack the understanding of the function of a given class of cells or the planning of new experiments.We must take care, therefore,while we simplify connections and functions in order to build a model which can account at best in part for the experimental results, that we do not oversimplify,and end up with what can only be referred to as a simple-minded model."(1976,p.1139).

Previously,a simple,informal interpretation of the meaning of probability summation was suggested. In this interpretation, the predictions based upon the latter are taken to correspond to conditions of equilibrium in a network of communicating units,and the deviations from this equilibrium are interpreted as net gains of different sign which emerge from complex weighting processes.

This suggestion was meant to combine the euristic value so far displayed by the notion of probability summation with a more dynamic interpretation of the phenomena it addresses.

It would not be surprising,though, if in the near future this notion,by virtue of its close kinship to the classic single-cell approach,will also reveal itself too "simple minded" to be longer considered as a valuable tool for the understanding of the functioning of a system that more and more reveals an integrated level of functioning that can no longer be ignored even when dealing with its simplest manifestations.

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